U.S. Global Change Research Program

Fourth National Climate Assessment

Volume II

Impacts, Risks, and Adaptation in the United States

Overview

Image credit

Front cover: *National Park Service*; **back cover:** *NASA Earth Observatory image by Joshua Stevens, using Landsat data from the U.S. Geological Survey.*

In August 2018, temperatures soared across the northwestern United States. The heat, combined with dry conditions, contributed to wildfire activity in several states and Canada. The cover shows the Howe Ridge Fire from across Lake McDonald in Montana's Glacier National Park on the night of August 12, roughly 24 hours after it was ignited by lightning. The fire spread rapidly, fueled by record-high temperatures and high winds, leading to evacuations and closures of parts of the park. The satellite image on the back cover, acquired on August 15, shows plumes of smoke from wildfires on the northwestern edge of Lake McDonald.

Wildfires impact communities throughout the United States each year. In addition to threatening individual safety and property, wildfire can worsen air quality locally and, in many cases, throughout the surrounding region, with substantial public health impacts including increased incidence of respiratory illness (Ch. 13: Air Quality, KM 2; Ch. 14: Health, KM 1; Ch. 26: Alaska, KM 3). As the climate warms, projected increases in wildfire frequency and area burned are expected to drive up costs associated with health effects, loss of homes and infrastructure, and fire suppression (Ch. 6: Forests, KM 1; Ch. 17: Complex Systems, Box 17.4). Increased wildfire activity is also expected to reduce the opportunity for and enjoyment of outdoor recreation activities, affecting quality of life as well as tourist economies (Ch. 7: Ecosystems, KM3; Ch. 13: Air Quality, KM 2; Ch. 14: Tribal, KM 1; Ch. 19: Southeast, KM3; Ch. 24: Northwest, KM 4).

Human-caused climate change, land use, and forest management influence wildfires in complex ways (Ch. 17: Complex Systems, KM 2). Over the last century, fire exclusion policies have resulted in higher fuel availability in most U.S. forests (CSSR, Ch. 8.3, KF 6). Warmer and drier conditions have contributed to an increase in the incidence of large forest fires in the western United States and Interior Alaska since the early 1980s, a trend that is expected to continue as the climate warms and the fire season lengthens (Ch. 1: Overview, Figure 1.2k; CSSR, Ch. 8.3, KF 6). The expansion of human activity into forests and other wildland areas has also increased over the past few decades. As the footprint of human settlement expands, fire risk exposure to people and property is expected to increase further (Ch. 5: Land Changes, KM 2).

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1 Overview

Howe Ridge Fire in Montana's Glacier National Park on August 12, 2018. *Photo credit: National Park Service.*

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Introduction

Earth's climate is now changing faster than at any point in the history of modern civilization, primarily as a result of human activities. The impacts of global climate change are already being felt in the United States and are projected to intensify in the future—but the severity of future impacts will depend largely on actions taken to reduce greenhouse gas emissions and to adapt to the changes that will occur. Americans increasingly recognize the risks climate change poses to their everyday lives and livelihoods and are beginning to respond (Figure 1.1). Water managers in the Colorado River Basin have mobilized users to conserve water in response to ongoing drought intensified by higher temperatures, and an extension program in Nebraska is helping ranchers reduce drought and heat risks to their operations. The state of Hawai'i is developing management options to promote coral reef recovery from widespread bleaching events caused by warmer waters that threaten tourism, fisheries, and coastal protection from wind and waves. To address higher risks of flooding from heavy rainfall, local governments in southern Louisiana are pooling hazard reduction funds, and cities and states in the Northeast are investing in more resilient water, energy, and transportation infrastructure. In Alaska, a tribal health organization is developing adaptation strategies to address physical and mental health challenges driven by climate change and other environmental changes. As Midwestern farmers adopt new management strategies to reduce erosion and nutrient losses caused by heavier rains, forest managers in the Northwest are developing adaptation strategies in response to wildfire increases that affect human health, water resources, timber production, fish and wildlife, and recreation. After extensive hurricane damage fueled in part by a warmer atmosphere and warmer, higher seas, communities in Texas are considering ways to rebuild more resilient infrastructure. In the U.S. Caribbean, governments are developing new frameworks for storm recovery based on lessons learned from the 2017 hurricane season.

Climate-related risks will continue to grow without additional action. Decisions made today determine risk exposure for current and future generations and will either broaden or limit options to reduce the negative consequences of climate change. While Americans are responding in ways that can bolster resilience and improve livelihoods, neither global efforts to mitigate the causes of climate change nor regional efforts to adapt to the impacts currently approach the scales needed to avoid substantial damages to the U.S. economy, environment, and human health and well-being over the coming decades.

Americans Respond to the Impacts of Climate Change

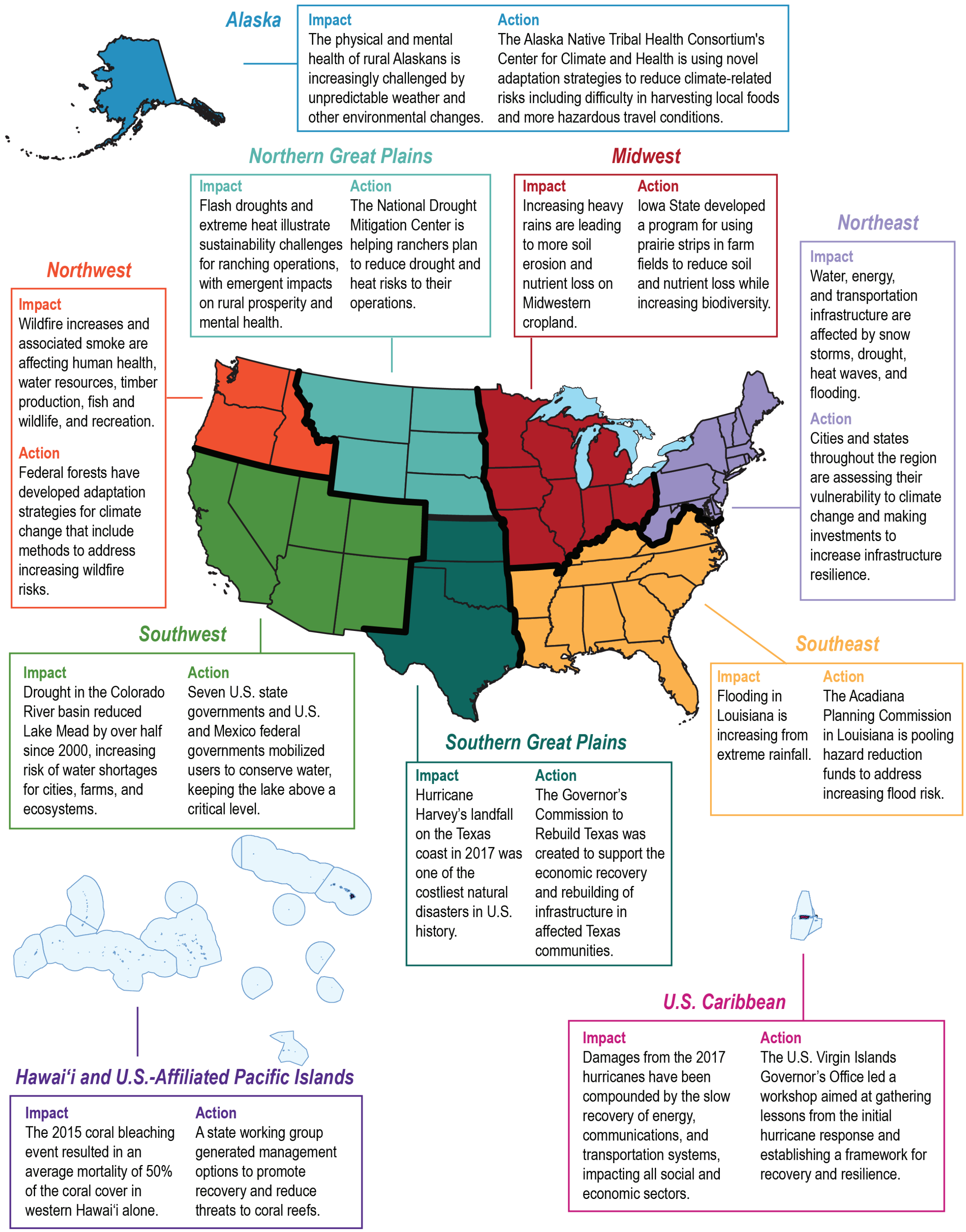


Figure 1.1: This map shows climate-related impacts that have occurred in each region since the Third National Climate Assessment in 2014 and response actions that are helping the region address related risks and costs. These examples are illustrative; they are not indicative of which impact is most significant in each region or which response action might be most effective. *Source: NCA4 Regional Chapters.*

Climate shapes where and how we live and the environment around us. Natural ecosystems, agricultural systems, water resources, and the benefits they provide to society are adapted to past climate conditions and their natural range of variability. A water manager may use past or current streamflow records to design a dam, a city could issue permits for coastal development based on current flood maps, and an electric utility or a farmer may invest in equipment suited to the current climate, all with the expectation that their investments and management practices will meet future needs.

However, the assumption that current and future climate conditions will resemble the recent past is no longer valid (Ch. 28: Adaptation, KM 2). Observations collected around the world provide significant, clear, and compelling evidence that global average temperature is much higher, and is rising more rapidly, than anything modern civilization has experienced, with widespread and growing impacts (Figure 1.2) (CSSR, Ch. 1.9). The warming trend observed over the past century can only be explained by the effects that human activities, especially emissions of greenhouse gases, have had on the climate (Ch. 2: Climate, KM 1 and Figure 2.1).

Climate change is transforming where and how we live and presents growing challenges to human health and quality of life, the economy, and the natural systems that support us. Risks posed by climate variability and change vary by region and sector and by the vulnerability of people experiencing impacts. Social, economic, and geographic factors shape the exposure of people and communities to climate-related impacts and their capacity to respond. Risks are often highest for those that are already vulnerable, including low-income communities, some communities of color, children, and the elderly (Ch. 14: Human Health, KM 2; Ch. 15: Tribes, KMs 1–3; Ch. 28: Adaptation, Introduction). Climate change threatens to exacerbate existing social and economic inequalities that result in higher exposure and sensitivity to extreme weather and climate-related events and other changes (Ch. 11: Urban, KM 1). Marginalized populations may also be affected disproportionately by actions to address the underlying causes and impacts of climate change, if they are not implemented under policies that consider existing inequalities (Ch. 11: Urban, KM 4; Ch. 28: Adaptation, KM 4).

This report draws a direct connection between the warming atmosphere and the resulting changes that affect Americans' lives, communities, and livelihoods, now and in the future. It documents vulnerabilities, risks, and impacts associated with natural climate variability and human-caused climate change across the United States and provides examples of response actions underway in many communities. It concludes that *the evidence of human-caused climate change is overwhelming and continues to strengthen, that the impacts of climate change are intensifying across the country, and that climate-related threats to Americans' physical, social, and economic well-being are rising*. These impacts are projected to intensify—but how much they intensify will depend on actions taken to reduce global greenhouse gas emissions and to adapt to the risks from climate change now and in the coming decades (Ch. 28: Adaptation, Introduction; Ch. 29: Mitigation, KMs 3 and 4).

Our Changing Climate: Observations, Causes, and Future Change

Observed Change

Observations from around the world show the widespread effects of increasing greenhouse gas concentrations on Earth's climate. High temperature extremes and heavy precipitation events are increasing. Glaciers and snow cover are shrinking, and sea ice is retreating. Seas are warming, rising, and becoming more acidic, and marine species are moving to new locations toward cooler waters. Flooding is becoming more frequent along the U.S. coastline. Growing seasons are lengthening, and wildfires are increasing. These and many other changes are clear signs of a warming world (Figure 1.2) (Ch. 2: Climate, Box 2.2; App. 3: Data & Scenarios, see also the USGCRP Indicators and EPA Indicators web sites).

California Drought Affects Mountain Snowpack

California's recent multiyear drought left Tioga Pass in the Sierra Nevada mountain range nearly snowless at the height of winter in January 2015. *Photo credit: Bartshé Miller.*

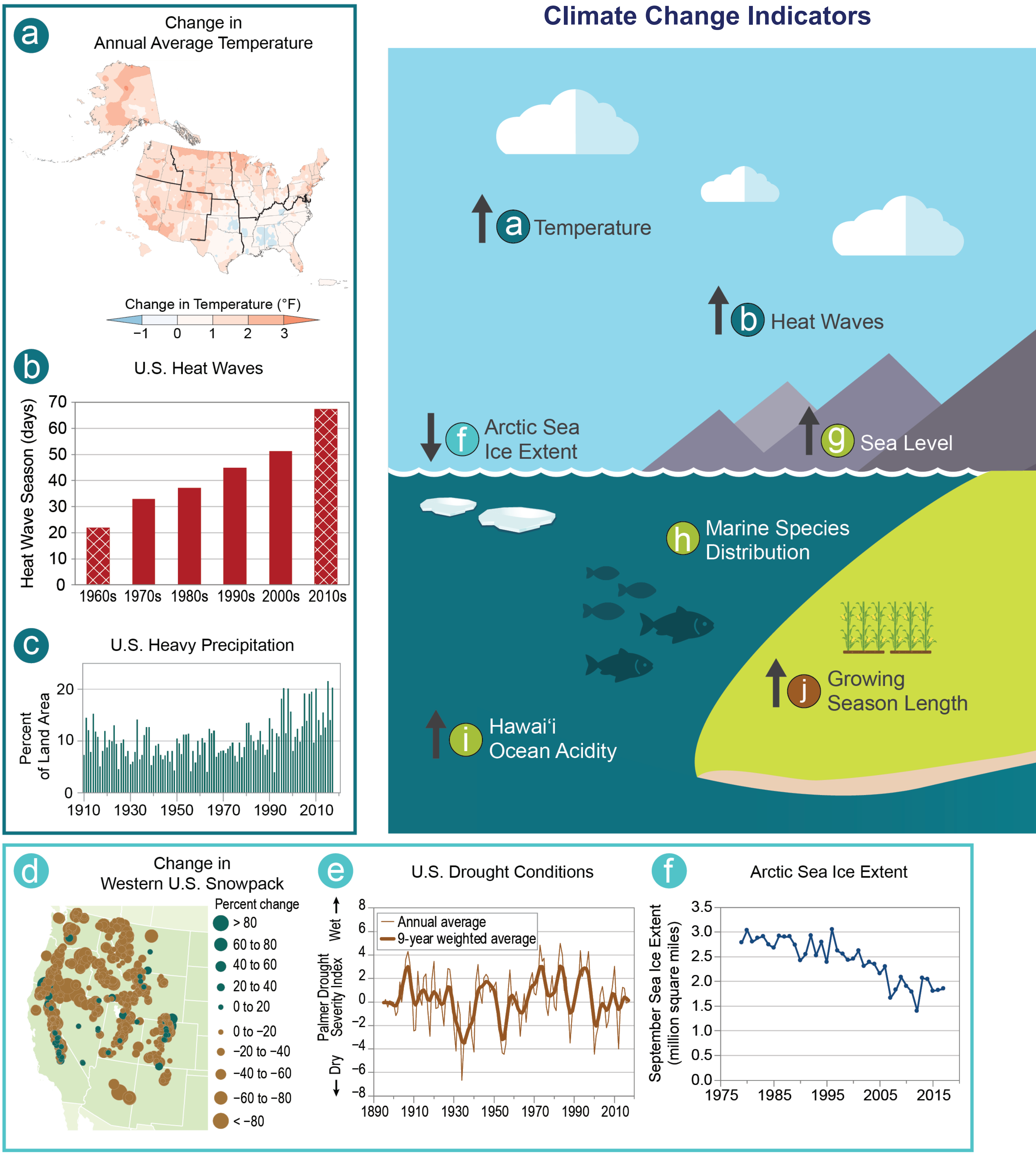
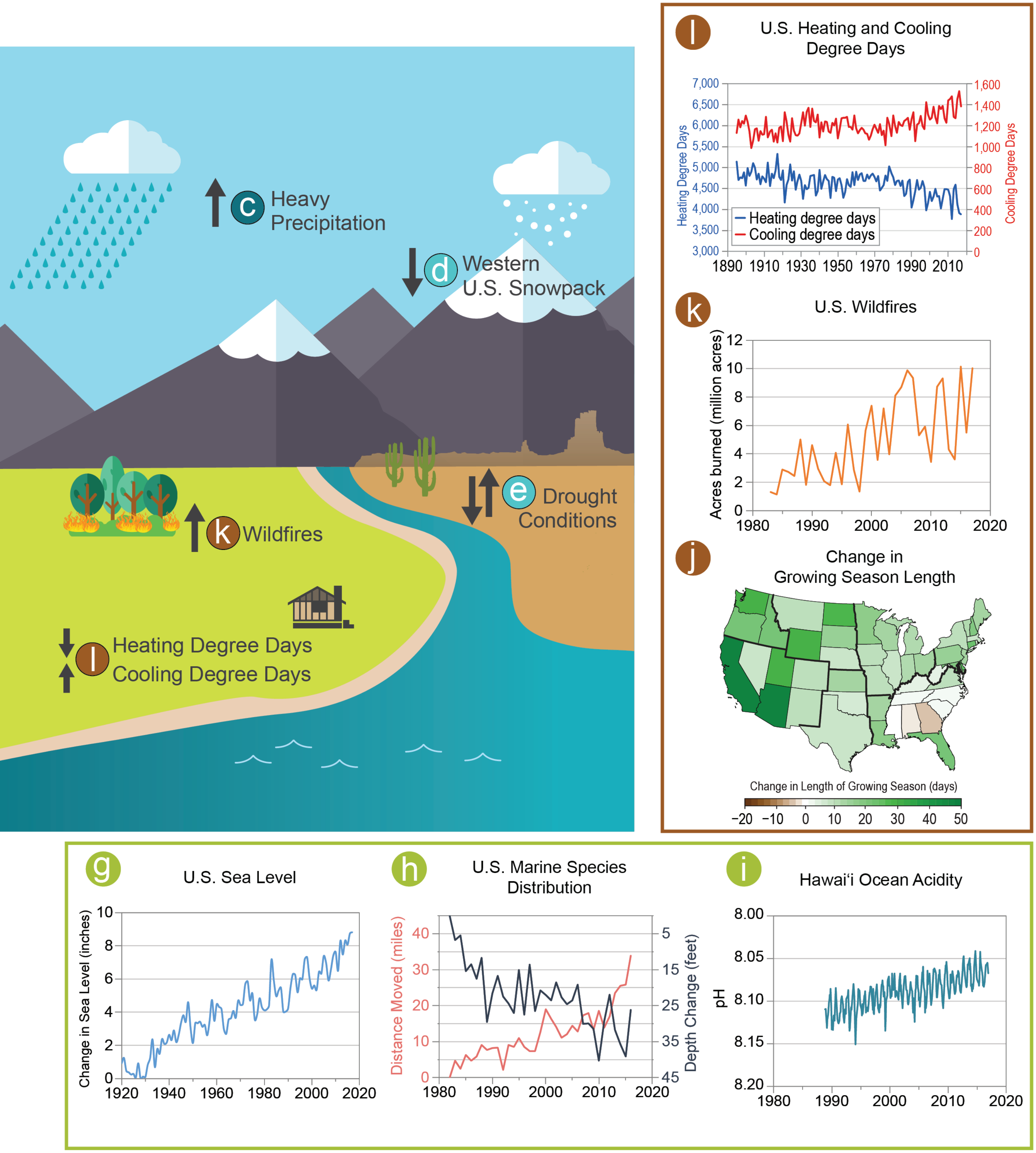


Figure 1.2: Long-term observations demonstrate the warming trend in the climate system and the effects of increasing atmospheric greenhouse gas concentrations (Ch. 2: Climate, Box 2.2). This figure shows climate-relevant indicators of change



based on data collected across the United States. Upward-pointing arrows indicate an increasing trend; downward-pointing arrows indicate a decreasing trend. Bidirectional arrows (e.g., for drought conditions) indicate a lack of a definitive national trend.

(Figure caption continued on next page)

Atmosphere (a–c): (a) Annual average temperatures have increased by 1.8°F across the contiguous United States since the beginning of the 20th century; this figure shows observed change for 1986–2016 (relative to 1901–1960 for the contiguous United States and 1925–1960 for Alaska, Hawai'i, Puerto Rico, and the U.S. Virgin Islands). Alaska is warming faster than any other state and has warmed twice as fast as the global average since the mid-20th century (Ch. 2: Climate, KM 5; Ch. 26: Alaska, Introduction). (b) The season length of heat waves in many U.S. cities has increased by over 40 days since the 1960s. Hatched bars indicate partially complete decadal data. (c) The relative amount of annual rainfall that comes from large, single-day precipitation events has changed over the past century; since 1910, a larger percentage of land area in the contiguous United States receives precipitation in the form of these intense single-day events.

Ice, snow, and water (d–f): (d) Large declines in snowpack in the western United States occurred from 1955 to 2016. (e) While there are a number of ways to measure drought, there is currently no detectable change in long-term U.S. drought statistics using the Palmer Drought Severity Index. (f) Since the early 1980s, the annual minimum sea ice extent (observed in September each year) in the Arctic Ocean has decreased at a rate of 11%–16% per decade (Ch. 2: Climate, KM 7).

Oceans and coasts (g–i): (g) Annual median sea level along the U.S. coast (with land motion removed) has increased by about 9 inches since the early 20th century as oceans have warmed and land ice has melted (Ch. 2: Climate, KM 4). (h) Fish, shellfish, and other marine species along the Northeast coast and in the eastern Bering Sea have, on average, moved northward and to greater depths toward cooler waters since the early 1980s (records start in 1982). (i) Oceans are also currently absorbing more than a quarter of the carbon dioxide emitted to the atmosphere annually by human activities, increasing their acidity (measured by lower pH values; Ch. 2: Climate, KM 3).

Land and ecosystems (j–l): (j) The average length of the growing season has increased across the contiguous United States since the early 20th century, meaning that, on average, the last spring frost occurs earlier and the first fall frost arrives later; this map shows changes in growing season length at the state level from 1895 to 2016. (k) Warmer and drier conditions have contributed to an increase in large forest fires in the western United States and Interior Alaska over the past several decades (CSSR, Ch. 8.3). (l) Degree days are defined as the number of degrees by which the average daily temperature is higher than 65°F (cooling degree days) or lower than 65°F (heating degree days) and are used as a proxy for energy demands for cooling or heating buildings. Changes in temperatures indicate that heating needs have decreased and cooling needs have increased in the contiguous United States over the past century.

Sources: (a) adapted from Vose et al. 2017, (b) EPA, (c–f and h–l) adapted from EPA 2016, (g and center infographic) EPA and NOAA.

Causes of Change

Scientists have understood the fundamental physics of climate change for almost 200 years. In the 1850s, researchers demonstrated that carbon dioxide and other naturally occurring greenhouse gases in the atmosphere prevent some of the heat radiating from Earth's surface from escaping to space: this is known as the greenhouse effect. This natural greenhouse effect warms the planet's surface about 60°F above what it would be otherwise, creating a habitat suitable for life. Since the late 19th century, however, humans have released an increasing amount of greenhouse gases into the atmosphere through burning fossil fuels and, to a lesser extent, deforestation and land-use change. As a result, the atmospheric concentration of carbon dioxide, the largest contributor to human-caused warming, has increased by about 40% over the industrial era. This change has intensified the natural greenhouse effect, driving an increase in global surface temperatures and other widespread changes in Earth's climate that are unprecedented in the history of modern civilization.

Global climate is also influenced by natural factors that determine how much of the sun's energy enters and leaves Earth's atmosphere and by natural climate cycles that affect temperatures and weather patterns in the short term, especially regionally (see Ch. 2: Climate, Box 2.1). However, the unambiguous long-term warming trend in global average temperature over the last century cannot be explained by natural factors alone. Greenhouse

gas emissions from human activities are the only factors that can account for the observed warming over the last century; there are no credible alternative human or natural explanations supported by the observational evidence. Without human activities, the influence of natural factors alone would actually have had a slight cooling effect on global climate over the last 50 years (Ch. 2: Climate, KM 1, Figure 2.1).

Future Change

Greenhouse gas emissions from human activities will continue to affect Earth's climate for decades and even centuries. Humans are adding carbon dioxide to the atmosphere at a rate far greater than it is removed by natural processes, creating a long-lived reservoir of the gas in the atmosphere and oceans that is driving the climate to a warmer and warmer state. Some of the other greenhouse gases released by human activities, such as methane, are removed from the atmosphere by natural processes more quickly than carbon dioxide; as a result, efforts to cut emissions of these gases could help reduce the rate of global temperature increases over the next few decades. However, longer-term changes in climate will largely be determined by emissions and atmospheric concentrations of carbon dioxide and other longer-lived greenhouse gases (Ch. 2: Climate, KM 2).

Climate models representing our understanding of historical and current climate conditions are often used to project how our world will change under future conditions (see Ch. 2: Climate, Box 2.7). "Climate" is defined as weather conditions over multiple decades, and climate model projections are generally not designed to capture annual or even decadal variation in climate conditions. Instead, projections are typically used to capture long-term changes, such as how the climate system will respond to changes in greenhouse gas levels over this century. Scientists test climate models by comparing them to current observations and historical changes. Confidence in these models is based, in part, on how well they reproduce these observed changes. Climate models have proven remarkably accurate in simulating the climate change we have experienced to date, particularly in the past 60 years or so when we have greater confidence in observations (see CSSR, Ch. 4.3.1). The observed signals of a changing climate continue to become stronger and clearer over time, giving scientists increased confidence in their findings even since the Third National Climate Assessment was released in 2014.

Today, the largest uncertainty in projecting future climate conditions is the level of greenhouse gas emissions going forward. Future global greenhouse gas emissions levels and resulting impacts depend on economic, political, and demographic factors that can be difficult to predict with confidence far into the future. Like previous climate assessments, NCA4 relies on a suite of possible scenarios to evaluate the implications of different climate outcomes and associated impacts throughout the 21st century. These "Representative Concentration Pathways" (RCPs) capture a range of potential greenhouse gas emissions pathways and associated atmospheric concentration levels through 2100.

RCPs drive climate model projections for temperature, precipitation, sea level, and other variables under futures that have either lower or higher greenhouse gas emissions. RCPs are numbered according to changes in "radiative forcing" by 2100 relative to preindustrial conditions: +2.6, +4.5, +6.0, or +8.5 watts per square

Box 1.1: Confidence and Uncertainty in Climate Science

Many of the decisions we make every day are based on less-than-perfect knowledge. For example, while GPS-based applications on smartphones can provide a travel-time estimate for our daily drive to work, an unexpected factor like a sudden downpour or fender bender might mean a ride originally estimated to be 20 minutes could actually take longer. Fortunately, even with this uncertainty we are confident that our trip is unlikely to take less than 20 minutes or more than half an hour—and we know where we are headed. We have enough information to plan our commute.

Uncertainty is also a part of science. A key goal of scientific research is to increase our confidence and reduce the uncertainty in our understanding of the world around us. Even so, there is no expectation that uncertainty can be fully eliminated, just as we do not expect a perfectly accurate estimate for our drive time each day. Studying Earth's climate system is particularly challenging because it integrates many aspects of a complex natural system as well as many human-made systems. Climate scientists find varying ranges of uncertainty in many areas, including observations of climate variables, the analysis and interpretation of those measurements, the development of new observational instruments, and the use of computer-based models of the processes governing Earth's climate system. While there is inherent uncertainty in climate science, there is high confidence in our understanding of the greenhouse effect and the knowledge that human activities are changing the climate in unprecedented ways. There is enough information to make decisions based on that understanding.

Where important uncertainties do exist, efforts to quantify and report those uncertainties can help decision-makers plan for a range of possible future outcomes. These efforts also help scientists advance understanding and ultimately increase confidence in and the usefulness of model projections. Assessments like this one explicitly address scientific uncertainty associated with findings and use specific language to express it to improve relevance to risk analysis and decision-making (see Front Matter and Box 1.2).

meter (W/m^2). Each RCP leads to a different level of projected global temperature change; higher numbers indicate greater projected temperature change and associated impacts. The higher scenario (RCP8.5) represents a future where annual greenhouse gas emissions increase significantly throughout the 21st century before leveling off by 2100, whereas the other RCPs represent more rapid and substantial mitigation by mid-century, with greater reductions thereafter. Current trends in annual greenhouse gas emissions, globally, are consistent with RCP8.5.

Of the two RCPs predominantly referenced throughout this report, the lower scenario (RCP4.5) envisions about 85% lower greenhouse gas emissions than the higher scenario (RCP8.5) by the end of the 21st century (see Ch. 2: Climate, Figure 2.2). In some cases, throughout this report, a very low scenario (RCP2.6) that represents more immediate, substantial, and sustained emissions reductions is considered. Each RCP could be consistent with a range of underlying socioeconomic conditions or policy choices. See the Scenario Products section of Appendix 3 in this report, as well as CSSR Chapters 4.2.1 and 10.2.1 for more detail.

The effects of different future greenhouse gas emissions levels on global climate become most evident around 2050, when temperature (Figure

Projected Changes in U.S. Annual Average Temperatures

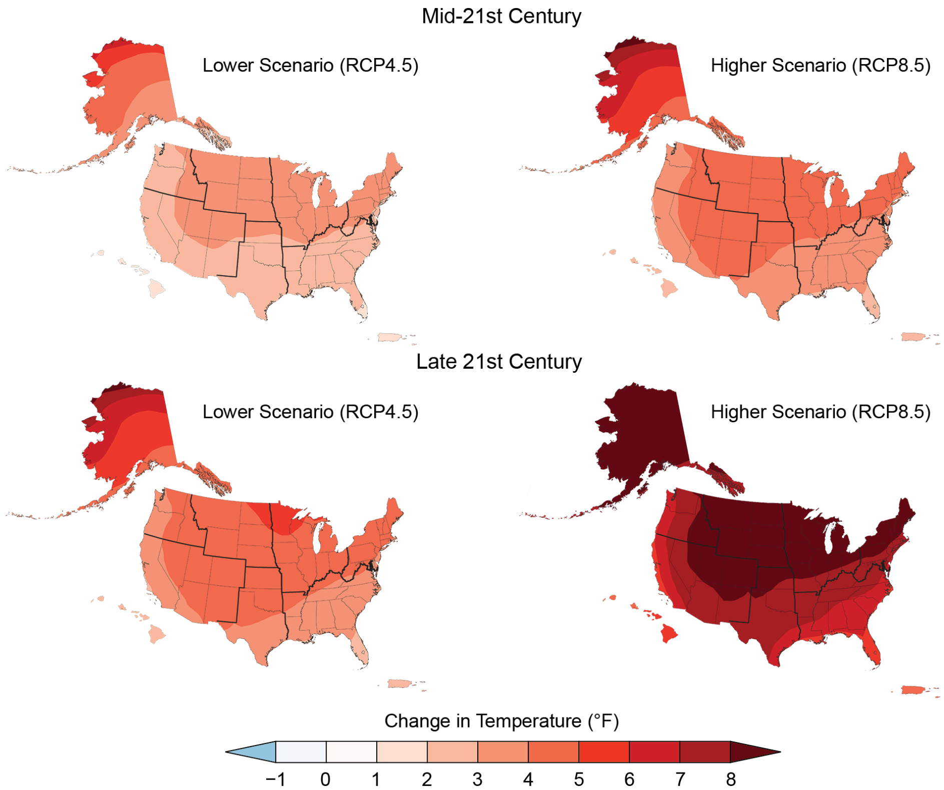


Figure 1.3: Annual average temperatures across the United States are projected to increase over this century, with greater changes at higher latitudes as compared to lower latitudes, and under a higher scenario (RCP8.5; right) than under a lower one (RCP4.5; left). This figure shows projected differences in annual average temperatures for mid-century (2036–2065; top) and end of century (2071–2100; bottom) relative to the near present (1986–2015). *From Figure 2.4, Ch. 2: Climate (Source: adapted from Vose et al. 2017).*

1.3) (Ch. 2: Climate, Figure 2.2), precipitation, and sea level rise (Figure 1.4) (Ch. 2: Climate, Figure 2.3) projections based on each scenario begin to diverge significantly. With substantial and sustained reductions in greenhouse gas emissions (e.g., consistent with the very low scenario [RCP2.6]), the increase in global annual average temperature relative to preindustrial times could be limited to less than 3.6°F (2°C) (Ch. 2: Climate, Box 2.4; CSSR, Ch. 4.2.1). Without significant greenhouse gas mitigation, the increase in global annual average temperature could reach 9°F or more by the end of this century (Ch. 2: Climate, KM 2). For some aspects of Earth's climate system that take longer to respond to changes in atmospheric greenhouse gas concentrations, such as global sea level, some degree of long-term change will be locked in for centuries to come, regardless of the future scenario (see CSSR, Ch. 12.5.3). Early greenhouse gas emissions mitigation can reduce climate impacts in the nearer term (such as reducing the loss of arctic sea ice and the effects on species that use it) and in the longer term by avoiding critical thresholds (such as marine ice sheet instability and the resulting consequences for global sea level and coastal development; Ch. 29: Mitigation, Timing and Magnitude of Action).

Annual average temperatures in the United States are projected to continue to increase in the coming decades. Regardless of future scenario, additional increases in temperatures

Projected Relative Sea Level Change in the United States by 2100

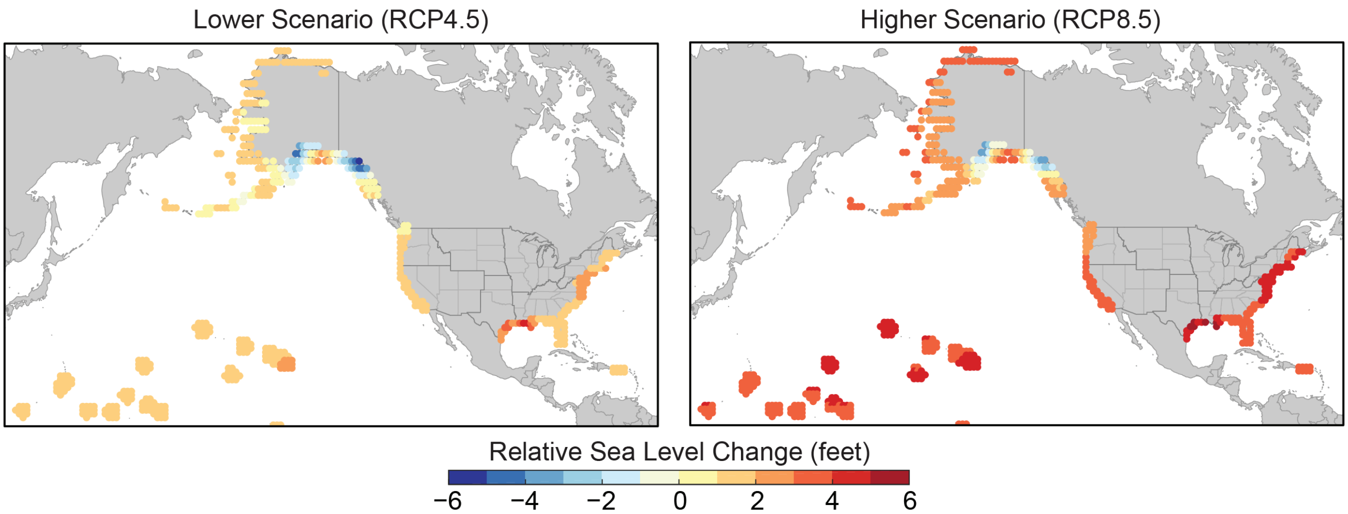


Figure 1.4: The maps show projections of change in relative sea level along the U.S. coast by 2100 (as compared to 2000) under the lower (RCP4.5) and higher (RCP8.5) scenarios (see CSSR, Ch. 12.5). Globally, sea levels will continue to rise from thermal expansion of the ocean and melting of land-based ice masses (such as Greenland, Antarctica, and mountain glaciers). Regionally, however, the amount of sea level rise will not be the same everywhere. Where land is sinking (as along the Gulf of Mexico coastline), relative sea level rise will be higher, and where land is rising (as in parts of Alaska), relative sea level rise will be lower. Changes in ocean circulation (such as the Gulf Stream) and gravity effects due to ice melt will also alter the heights of the ocean regionally. Sea levels are expected to continue to rise along almost all U.S. coastlines, and by 2100, under the higher scenario, coastal flood heights that today cause major damages to infrastructure would become common during high tides nationwide (Ch. 8: Coastal; Scenario Products section in Appendix 3). *Source: adapted from CSSR, Figure 12.4*.

across the contiguous United States of at least 2.3°F relative to 1986–2015 are expected by the middle of this century. As a result, recent record-setting hot years are expected to become common in the near future. By late this century, increases of 2.3°–6.7°F are expected under a lower scenario (RCP4.5) and 5.4°–11.0°F under a higher scenario (RCP8.5) relative to 1986–2015 (Figure 1.3) (Ch. 2: Climate, KM 5, Figure 2.4). Alaska has warmed twice as fast as the global average since the mid-20th century; this trend is expected to continue (Ch. 26: Alaska, Introduction).

High temperature extremes, heavy precipitation events, high tide flooding events along the U.S. coastline, ocean acidification and warming, and forest fires in the western United States and Alaska are all projected to continue to increase, while land and sea ice cover, snowpack, and surface soil moisture are expected to continue to decline in the coming decades. These and other changes are expected to increasingly impact water resources, air quality, human health, agriculture, natural ecosystems, energy and transportation infrastructure, and many other natural and human systems that support communities across the country. The severity of these projected impacts, and the risks they present to society, is greater under futures with higher greenhouse gas emissions, especially if limited or no adaptation occurs (Ch. 29: Mitigation, KM 2).

Box 1.2: Evaluating Risks to Inform Decisions

In this report, *risks* are often defined in a qualitative sense as threats to life, health and safety, the environment, economic well-being, and other things of value to society (Ch. 28: Adaptation, Introduction). In some cases, risks are described in quantitative terms: estimates of how likely a given threat is to occur (probability) and the damages that would result if it did happen (consequences). Climate change is a risk management challenge for society; it presents uncertain—and potentially severe—consequences for natural and human systems across generations. It is characterized by multiple intersecting and uncertain future hazards and, therefore, acts as a risk multiplier that interacts with other stressors to create new risks or to alter existing ones (see Ch. 17: Complex Systems, KM 1).

Current and future greenhouse gas emissions, and thus mitigation actions to reduce emissions, will largely determine future climate change impacts and risks to society. Mitigation and adaptation activities can be considered complementary strategies—mitigation efforts can reduce future risks, while adaptation can minimize the consequences of changes that are already happening as a result of past and present greenhouse gas emissions. Adaptation entails proactive decision-making and investments by individuals, businesses, and governments to counter specific risks from climate change that vary from place to place. Climate risk management includes some familiar attributes and tactics for most businesses and local governments, which often manage or design for a variety of weather-related risks, including coastal and inland storms, heat waves, threats to water availability, droughts, and floods.

Measuring risk encompasses both likelihoods and consequences of specific outcomes and involves judgments about what is of value, ranking of priorities, and cost–benefit analyses that incorporate the tradeoffs among climate and non-climate related options. This report characterizes specific risks across regions and sectors in an effort to help people assess the risks they face, create and implement a response plan, and monitor and evaluate the efficacy of a given action (see Ch. 28: Adaptation, KM 1, Figure 28.1).

Climate Change in the United States: Current and Future Risks

Some climate-related impacts, such as increasing health risks from extreme heat, are common to many regions of the United States (Ch. 14: Human Health, KM 1). Others represent more localized risks, such as infrastructure damage caused by thawing of permafrost (long-frozen ground) in Alaska or threats to coral reef ecosystems from warmer and more acidic seas in the U.S. Caribbean, as well as Hawai'i and the U.S.-Affiliated Pacific Islands (Ch. 26: Alaska, KM 2; Ch. 20: U.S. Caribbean, KM 2; Ch. 27: Hawai'i & Pacific Islands, KM 4).

Risks vary by both a community's exposure to physical climate impacts and by factors that influence their ability to respond to changing conditions and to recover from adverse weather and climate-related events such as extreme storms or wildfires (Ch. 14: Human Health, KM 2; Ch. 15: Tribes, State of the Sector, KMs 1 and 2; Ch. 28: Adaptation, KM 4).

Many places are subject to more than one climate-related impact, such as extreme rainfall combined with coastal flooding, or drought coupled with extreme heat, wildfire, and flooding. The compounding effects of these impacts result in increased risks to people, infrastructure, and interconnected economic

sectors (Ch. 11: Urban, KM 1). Impacts affecting interconnected systems can cascade across sectors and regions, creating complex risks and management challenges. For example, changes in the frequency, intensity, extent, and duration of wildfires can result in a higher instance of landslides that disrupt transportation systems and the flow of goods and services within or across regions (Box 1.3). Many observed impacts reveal vulnerabilities in these interconnected systems that are expected to be exacerbated as climate-related risks intensify. Under a higher scenario (RCP8.5), it is very likely that some impacts, such as the effects of ice sheet disintegration on sea level rise and coastal development, will be irreversible for many thousands of years, and others, such as species extinction, will be permanent (Ch. 7: Ecosystems, KM 1; Ch. 9: Oceans, KM 1; Ch. 29: Mitigation, KM 2).

Economy and Infrastructure

Without more significant global greenhouse gas mitigation and regional adaptation efforts, climate change is expected to cause substantial losses to infrastructure and property and impede the rate of economic growth over this century (Ch. 4: Energy, KM 1; Ch. 8: Coastal, KM 1; Ch. 11: Urban, KM 2; Ch. 12: Transportation, KM 1; Regional Chapters 18–27). Regional economies and industries that depend on natural resources and favorable climate conditions, such as agriculture, tourism, and fisheries, are increasingly vulnerable to impacts driven by climate change (Ch. 7: Ecosystems, KM 3; Ch. 10: Agriculture, KM 1). Reliable and affordable energy supplies, which underpin virtually every sector of the economy, are increasingly at risk from climate change and weather extremes (Ch. 4: Energy, KM 1). The impacts of climate

Box 1.3: Interconnected Impacts of Climate Change

The impacts of climate change and extreme weather on natural and built systems are often considered from the perspective of individual sectors: how does a changing climate impact water resources, the electric grid, or the food system? None of these sectors, however, exists in isolation. The natural, built, and social systems we rely on are all interconnected, and impacts and management choices within one sector may have cascading effects on the others (Ch. 17: Complex Systems, KM 1).

For example, wildfire trends in the western United States are influenced by rising temperatures and changing precipitation patterns, pest populations, and land management practices. As humans have moved closer to forestlands, increased fire suppression practices have reduced natural fires and led to denser vegetation, resulting in fires that are larger and more damaging when they do occur (Figures 1.5 and 1.2k) (Ch. 6: Forests, KM 1). Warmer winters have led to increased pest outbreaks and significant tree kills, with varying feedbacks on wildfire. Increased wildfire driven by climate change is projected to increase costs associated with health effects, loss of homes and other property, wildfire response, and fuel management. Failure to anticipate these interconnected impacts can lead to missed opportunities for effectively managing risks within a single sector and may actually increase risks to other sectors. Planning around wildfire risk and other risks affected by climate change entails the challenge of accounting for all of these influences and how they interact with one another (see Ch. 17: Complex Systems, Box 17.4).

Box 1.3: Interconnected Impacts of Climate Change, *continued*

New to this edition of the NCA, Chapter 17 (Complex Systems) highlights several examples of interconnected impacts and documents how a multisector perspective and joint management of systems can enhance resilience to a changing climate. It is often difficult or impossible to quantify and predict how all relevant processes and interactions in interconnected systems will respond to climate change. Non-climate influences, such as population changes, add to the challenges of projecting future outcomes (Ch. 17: Complex Systems, KM 2). Despite these challenges, there are opportunities to learn from experience to guide future risk management decisions. Valuable lessons can be learned retrospectively: after Superstorm Sandy in 2012, for example, the mayor of New York City initiated a Climate Change Adaptation Task Force that brought together stakeholders from several sectors such as water, transportation, energy, and communications to address the interdependencies among them (Ch. 17: Complex Systems, Box 17.1, KM 3).

Wildfire at the Wildland–Urban Interface

Figure 1.5: Wildfires are increasingly encroaching on American communities, posing threats to lives, critical infrastructure, and property. In October 2017, more than a dozen fires burned through northern California, killing dozens of people and leaving thousands more homeless. Communities distant from the fires were affected by poor air quality as smoke plumes darkened skies and caused the cancellation of school and other activities across the region. (left) A NASA satellite image shows active fires on October 9, 2017. (right) The Tubbs Fire, which burned parts of Napa, Sonoma, and Lake counties, was the most destructive in California's history. It caused an estimated $1.2 billion in damages and destroyed over 5,000 structures, including 5% of the housing stock in the city of Santa Rosa. *Credits: (left) NASA; (right) Master Sgt. David Loeffler, U.S. Air National Guard.*

change beyond our borders are expected to increasingly affect our trade and economy, including import and export prices and U.S. businesses with overseas operation and supply chains (Box 1.4) (Ch. 16: International, KM 1; Ch. 17: Complex Systems, KM 1). Some aspects of our economy may see slight improvements in a modestly warmer world. However, the continued warming that is projected to occur without significant reductions in global greenhouse gas emissions is expected to cause substantial net damage to the U.S. economy, especially in the absence of increased adaptation efforts. The potential for losses in some sectors could reach hundreds of billions of dollars per year by the end of this century (Ch. 29: Mitigation, KM 2).

Existing water, transportation, and energy infrastructure already face challenges from heavy rainfall, inland and coastal flooding, landslides, drought, wildfire, heat waves, and other weather and climate events (Figures 1.5–1.9)

(Ch. 11: Urban, KM 2; Ch. 12: Transportation, KM 1). Many extreme weather and climate-related events are expected to become more frequent and more intense in a warmer world, creating greater risks of infrastructure disruption and failure that can cascade across economic sectors (Ch. 3: Water, KM 2; Ch. 4: Energy, KM 1; Ch. 11: Urban, KM 3; Ch. 12: Transportation, KM 2). For example, more frequent and severe heat waves and other extreme events in many parts of the United States are expected to increase stresses on the energy system, amplifying the risk of more frequent and longer-lasting power outages and fuel shortages that could affect other critical sectors and systems, such as access to medical care (Ch. 17: Complex Systems, Box 17.5; Ch. 4: Energy, KM 1; Ch. 8: Coastal, KM 1; Ch. 11: Urban, KM 3; Ch. 12: Transportation, KM 3). Current infrastructure is typically designed for historical climate conditions (Ch. 12: Transportation, KM 1) and development patterns—for instance, coastal land use—generally do not account for a changing climate (Ch. 5: Land Changes, State of the Sector), resulting in increasing vulnerability to future risks from weather extremes and climate change (Ch. 11: Urban, KM 2). Infrastructure age and deterioration make failure or interrupted service from extreme weather even more likely (Ch. 11: Urban, KM 2). Climate change is expected to increase the costs of maintaining, repairing, and replacing infrastructure, with differences across regions (Ch. 12: Transportation, Regional Summary).

Recent extreme events demonstrate the vulnerabilities of interconnected economic sectors to increasing risks from climate change (see Box 1.3). In 2017, Hurricane Harvey dumped an unprecedented amount of rainfall over the greater Houston area, some of which has been attributed to human-induced climate change (Ch. 2: Climate, Box 2.5). Resulting power outages had cascading effects on critical infrastructure facilities such as hospitals and water and wastewater treatment plants. Reduced oil production and refining capacity in the Gulf of Mexico caused price spikes regionally and nationally from actual and anticipated gasoline shortages (Figure 1.6) (Ch. 17: Complex Systems, KM 1). In the U.S. Caribbean, Hurricanes Irma and Maria caused catastrophic damage to infrastructure, including the complete failure of Puerto Rico's power grid and the loss of power throughout the U.S. Virgin Islands, as well as extensive damage to the region's agricultural industry. The death toll in Puerto Rico grew in the three months following Maria's landfall on the island due in part to the lack of electricity and potable water as well as access to medical facilities and medical care (Ch. 20: U.S. Caribbean, Box 20.1, KM 5).

Climate-related risks to infrastructure, property, and the economy vary across regions. Along the U.S. coastline, public infrastructure and $1 trillion in national wealth held in coastal real estate are threatened by rising sea levels, higher storm surges, and the ongoing increase in high tide flooding (Figures 1.4 and 1.8) (Ch. 8: Coastal, KM 1). Coastal infrastructure provides critical lifelines to the rest of the country, including energy supplies and access to goods and services from overseas trade; increased damage to coastal facilities is expected to result in cascading costs and national impacts (Ch. 8: Coastal, KM 1; Ch. 4: Energy, State of the Sector, KM 1). High tide flooding is projected to become more disruptive and costlier as its frequency, depth, and inland extent grow in the coming decades. Without significant adaptation measures, many coastal cities in the Southeast are expected to experience daily high tide flooding by the end of the century (Ch. 8:

Widespread Impacts from Hurricane Harvey

Figure 1.6: Hurricane Harvey led to widespread flooding and knocked out power to 300,000 customers in Texas in 2017, with cascading effects on critical infrastructure facilities such as hospitals, water and wastewater treatment plants, and refineries. The photo shows Port Arthur, Texas, on August 31, 2017—six days after Hurricane Harvey made landfall along the Gulf Coast. *From Figure 17.2, Ch. 17: Complex Systems (Photo credit: Staff Sgt. Daniel J. Martinez, U.S. Air National Guard).*

Flooding at Fort Calhoun Nuclear Power Plant

Figure 1.7: Floodwaters from the Missouri River surround the Omaha Public Power District's Fort Calhoun Station, a nuclear power plant just north of Omaha, Nebraska, on June 20, 2011. The flooding was the result of runoff from near-record snowfall totals and record-setting rains in late May and early June. A protective berm holding back the floodwaters from the plant failed, which prompted plant operators to transfer offsite power to onsite emergency diesel generators. Cooling for the reactor temporarily shut down, but spent fuel pools were unaffected. *From Figure 22.5, Ch. 22: N. Great Plains (Photo credit: Harry Weddington, U.S. Army Corps of Engineers).*

Norfolk Naval Base at Risk from Rising Seas

Figure 1.8: Low-lying Norfolk, Virginia, houses the world's largest naval base, which supports multiple aircraft carrier groups and is the duty station for thousands of employees. Most of the area around the base lies less than 10 feet above sea level, and local relative sea level is projected to rise between about 2.5 and 11.5 feet by the year 2100 under the Lower and Upper Bound USGCRP sea level rise scenarios, respectively (see Scenario Products section of Appendix 3 for more details on these sea level rise scenarios; see also Ch. 8: Coastal, Case Study "Key Messages in Action: Norfolk, Virginia"). *Photo credit: Mass Communication Specialist 1st Class Christopher B. Stoltz, U.S. Navy*.

Coastal, KM 1; Ch. 19: Southeast, KM 2). Higher sea levels will also cause storm surge from tropical storms to travel farther inland than in the past, impacting more coastal properties and infrastructure (Ch. 8: Coastal: KM 1; Ch. 19: Southeast, KM 2). Oil, natural gas, and electrical infrastructure located along the coasts of the Atlantic Ocean and Gulf of Mexico are at increased risk of damage from rising sea levels and stronger hurricanes; regional disruptions are expected to have national implications (Ch. 4: Energy, State of the Sector, KM 1; Ch.

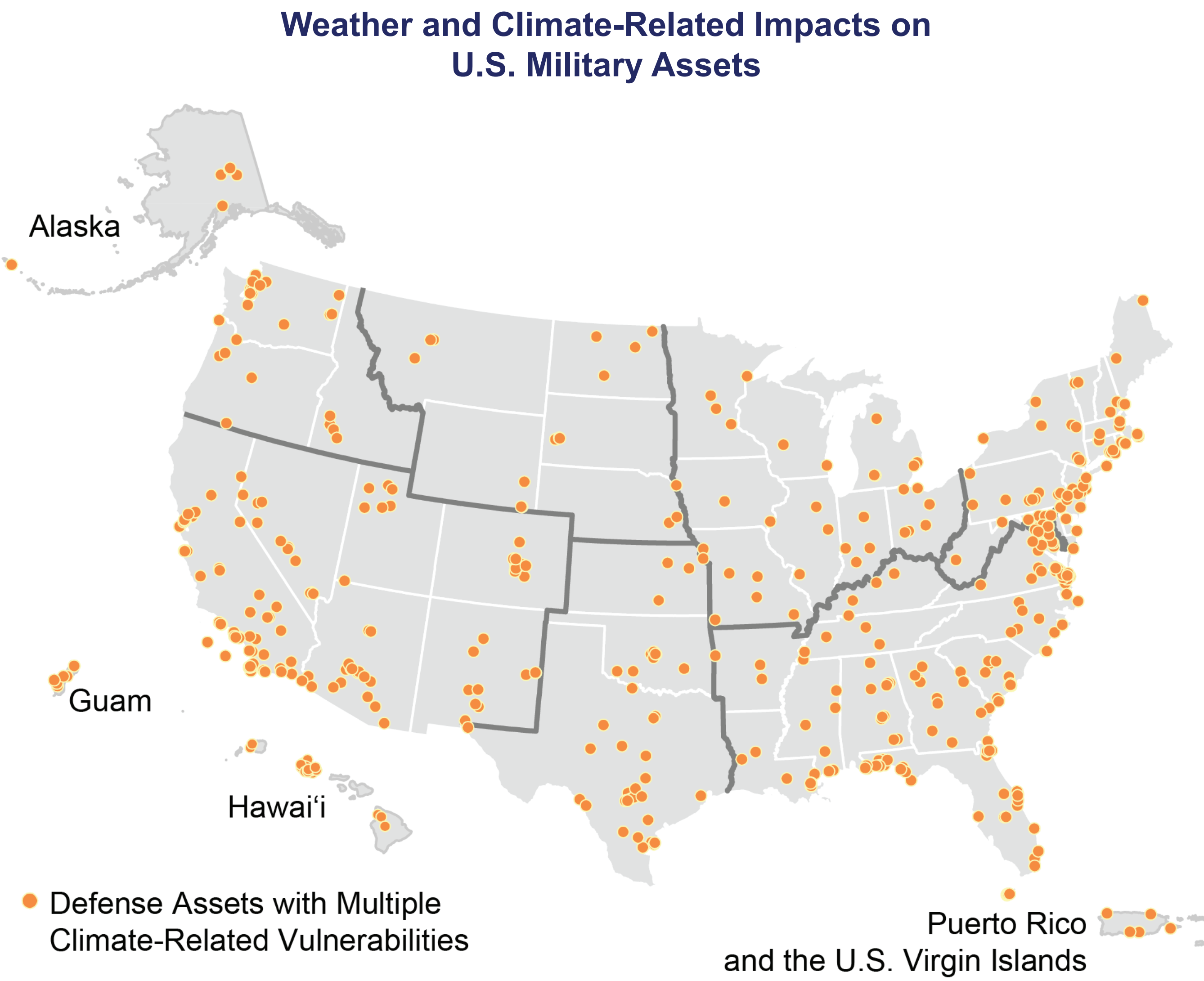


Figure 1.9: The Department of Defense (DoD) has significant experience in planning for and managing risk and uncertainty. The effects of climate and extreme weather represent additional risks to incorporate into the Department's various planning and risk management processes. To identify DoD installations with vulnerabilities to climate-related impacts, a preliminary Screening Level Vulnerability Assessment Survey (SLVAS) of DoD sites worldwide was conducted in 2015. The SLVAS responses (shown for the United States; orange dots) yielded a wide range of qualitative information. The highest number of reported effects resulted from drought (782), followed closely by wind (763) and non-storm surge related flooding (706). About 10% of sites indicated being affected by extreme temperatures (351), while flooding due to storm surge (225) and wildfire (210) affected about 6% of the sites reporting. The survey responses provide a preliminary qualitative picture of DoD assets currently affected by severe weather events as well as an indication of assets that may be affected by sea level rise in the future. *Source: adapted from Department of Defense 2018 (http://www.oea.gov/resource/2018-climate-related-risk-dod-infrastructure-initial-vulnerability-assessment-survey-slvas).*

18: Northeast, KM 3; Ch. 19: Southeast, KM 2). Hawai‘i and the U.S.-Affiliated Pacific Islands and the U.S. Caribbean also face high risks to critical infrastructure from coastal flooding, erosion, and storm surge (Ch. 4: Energy, State of the Sector; Ch. 20: U.S. Caribbean, KM 3; Ch. 27: Hawai‘i & Pacific Islands, KM 3).

In the western United States, increasing wildfire is damaging ranches and rangelands as well as property in cities near the wildland–urban interface. Drier conditions are projected to increase the risk of wildfires and damage to property and infrastructure, including energy production and generation assets and the power grid (Ch. 4: Energy, KM 1; Ch. 11: Urban, Regional Summary; Ch. 24: Northwest, KM 3). In Alaska, thawing of permafrost is responsible for severe damage to roads, buildings, and pipelines that will be costly to replace, especially in remote parts of Alaska. Alaska oil and gas operations are vulnerable to thawing permafrost, sea level rise, and increased coastal exposure due to declining sea ice; however, a longer ice-free season may enhance offshore energy operations and transport (Ch. 4: Energy, State of the Sector; Ch. 26: Alaska, KMs 2 and 5). These impacts are expected to grow with continued warming.

U.S. agriculture and the communities it supports are threatened by increases in temperatures, drought, heavy precipitation events, and wildfire on rangelands (Figure 1.10) (Ch. 10: Ag & Rural, KMs 1 and 2, Case Study "Groundwater Depletion in the Ogallala Aquifer Region"; Ch. 23: S. Great Plains, KM 1, Case Study "The Edwards Aquifer"). Yields of major U.S. crops (such as corn, soybeans, wheat, rice, sorghum, and cotton) are expected to decline over this century as a consequence of increases in temperatures and possibly changes in water availability and disease and pest outbreaks (Ch. 10: Ag & Rural, KM 1). Increases in growing season temperatures in the Midwest are projected to be the largest contributing factor to declines in U.S. agricultural productivity (Ch. 21: Midwest, KM 1). Climate change is also expected to lead to large-scale shifts in the availability and prices of many agricultural products across the world, with corresponding impacts on U.S. agricultural producers and the U.S. economy (Ch. 16: International, KM 1).

Conservation Practices Reduce Impact of Heavy Rains

Figure 1.10: Increasing heavy rains are leading to more soil erosion and nutrient loss on midwestern cropland. Integrating strips of native prairie vegetation into row crops has been shown to reduce soil and nutrient loss while improving biodiversity. The inset shows a close-up example of a prairie vegetation strip. *From Figure 21.2, Ch. 21: Midwest (Photo credits: [main photo] Lynn Betts; [inset] Farnaz Kordbacheh).*

Extreme heat poses a significant risk to human health and labor productivity in the agricultural, construction, and other outdoor sectors (Ch. 10: Ag & Rural, KM 3). Under a higher scenario (RCP8.5), almost two billion labor hours are projected to be lost annually by 2090 from the impacts of temperature extremes, costing an estimated $160 billion in lost wages (Ch. 14: Human Health, KM 4). States within the Southeast (Ch. 19: Southeast, KM 4) and Southern Great Plains (Ch. 23: S. Great Plains, KM 4)

regions are projected to experience some of the greatest impacts (see Figure 1.21).

Natural Environment and Ecosystem Services

Climate change threatens many benefits that the natural environment provides to society: safe and reliable water supplies, clean air, protection from flooding and erosion, and the use of natural resources for economic, recreational, and subsistence activities. Valued aspects of regional heritage and quality of life tied to the natural environment, wildlife, and outdoor recreation will change with the climate, and as a result, future generations can expect to experience and interact with natural systems in ways that are much different than today. Without significant reductions in greenhouse gas emissions, extinctions and transformative impacts on some ecosystems cannot be avoided, with varying impacts on the economic, recreational, and subsistence activities they support.

Changes affecting the quality, quantity, and availability of water resources, driven in part by climate change, impact people and the environment (Ch. 3: Water, KM 1). Dependable and safe water supplies for U.S. Caribbean, Hawai‘i, and U.S.-Affiliated Pacific Island communities and ecosystems are threatened by rising temperatures, sea level rise, saltwater intrusion, and increased risks of drought and flooding (Ch. 3: Water, Regional Summary; Ch. 20: U.S. Caribbean, KM 1; Ch. 27: Hawai‘i & Pacific Islands, KM 1). In the Midwest, the occurrence of conditions that contribute to harmful algal blooms, which can result in restrictions to water usage for drinking and recreation, are expected to increase (Ch. 3: Water, Regional Summary; Ch. 21: Midwest, KM 3). In the Southwest, water supplies for people and nature are decreasing during droughts due in part to climate change. Intensifying droughts, heavier downpours, and reduced snowpack are combining with other stressors such as groundwater depletion to reduce the future reliability of water supplies in the region, with cascading impacts on energy production and other water-dependent sectors (Ch. 3: Water, Regional Summary; Ch. 4: Energy, State of the Sector; Ch. 25: Southwest, KM 5). In the Southern Great Plains, current drought and projected increases in drought length and severity threaten the availability of water for agriculture (Figures 1.11 and 1.12)(Ch. 23: S. Great Plains, KM 1). Reductions in mountain snowpack and shifts in snowmelt timing are expected to reduce hydropower production in the Southwest and the Northwest (Ch. 24: Northwest, KM 3; Ch. 25: Southwest, KM 5). Drought is expected to threaten oil and gas drilling and refining as well as thermoelectric power plants that rely on a steady supply of water for cooling (Ch. 4: Energy, State of the Sector, KM 1; Ch. 22: N. Great Plains, KM 4; Ch. 23: S. Great Plains, KM 2; Ch. 25: Southwest, KM 5).

Impacts of Drought on Texas Agriculture

Figure 1.11: Soybeans in Texas experience the effects of drought in August 2013. During 2010–2015, a multiyear regional drought severely affected agriculture in the Southern Great Plains. One prominent impact was the reduction of irrigation water released for farmers on the Texas coastal plains. *Photo credit: Bob Nichols, USDA*.

Desalination Plants Can Reduce Impacts from Drought in Texas

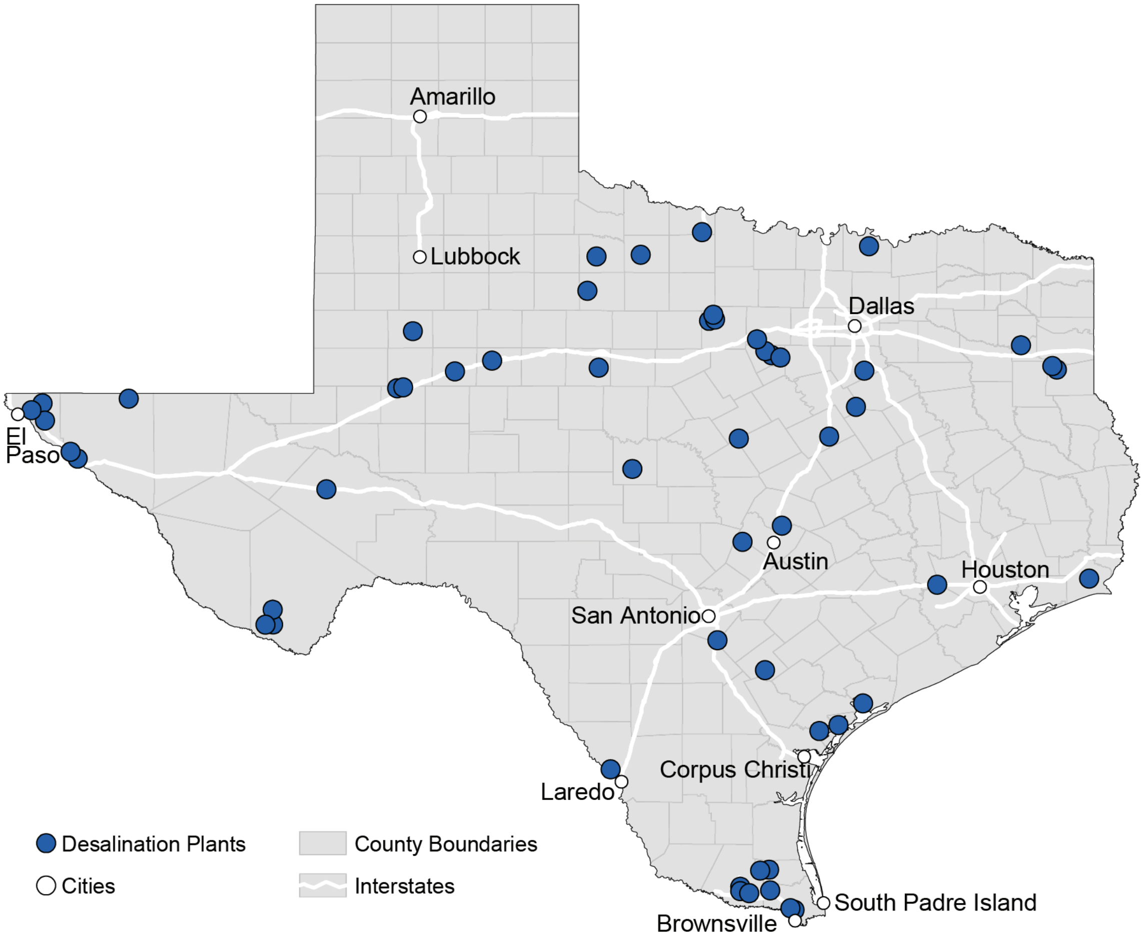


Figure 1.12: Desalination activities in Texas are an important contributor to the state's efforts to meet current and projected water needs for communities, industry, and agriculture. The state's 2017 Water Plan recommended an expansion of desalination to help reduce longer-term risks to water supplies from drought, higher temperatures, and other stressors. There are currently 44 public water supply desalination plants in Texas. *From Figure 23.8, Ch. 23: S. Great Plains (Source: adapted from Texas Water Development Board 2017)*.

Tourism, outdoor recreation, and subsistence activities are threatened by reduced snowpack, increases in wildfire activity, and other stressors affecting ecosystems and natural resources (Figures 1.2d, 1.2k, and 1.13) (Ch. 7: Ecosystems, KM 3). Increasing wildfire frequency (Ch. 19: Southeast, Case Study "Prescribed Fire"), pest and disease outbreaks (Ch. 21: Midwest, Case Study "Adaptation in Forestry"), and other stressors are projected to reduce the ability of U.S. forests to support recreation as well as economic and subsistence activities (Ch. 6: Forests, KMs 1 and 2; Ch. 19: Southeast, KM 3; Ch. 21: Midwest, KM 2). Increases in wildfire smoke events driven by climate change are expected to reduce the amount and quality of time spent in outdoor activities (Ch. 13: Air Quality, KM 2; Ch. 24: Northwest, KM 4). Projected declines in snowpack in the western United States and shifts to more precipitation falling as rain than snow in the cold season in many parts of the central and eastern United States are expected to adversely impact the winter recreation industry (Ch. 18: Northeast, KM 1; Ch. 22: N. Great Plains, KM 3; Ch. 24: Northwest, KM 1, Box 24.7). In the Northeast, activities that rely on natural snow and ice cover may not be economically viable by the

Razor Clamming on the Washington Coast

Figure 1.13: Razor clamming draws crowds on the coast of Washington. This popular recreation activity is expected to decline due to ocean acidification, harmful algal blooms, warmer temperatures, and habitat degradation. *From Figure 24.7, Ch. 24: Northwest (Photo courtesy of Vera Trainer, NOAA).*

end of the century without significant reductions in global greenhouse gas emissions (Ch. 18: Northeast, KM 1). Diminished snowpack, increased wildfire, pervasive drought, flooding, ocean acidification, and sea level rise directly threaten the viability of agriculture, fisheries, and forestry enterprises on tribal lands across the United States and impact tribal tourism and recreation sectors (Ch. 15: Tribes, KM 1).

Climate change has already had observable impacts on biodiversity and ecosystems throughout the United States that are expected to continue. Many species are shifting their ranges (Figure 1.2h), and changes in the timing of important biological events (such as migration and reproduction) are occurring in response to climate change (Ch. 7: Ecosystems, KM 1). Climate change is also aiding the spread of invasive species (Ch. 23: Midwest, Case Study "Adaptation in Forestry"; Ch. 22: N. Great Plains, Case Study "Crow Nation and the Spread of Invasive Species"), recognized as a major driver of biodiversity loss and substantial ecological and economic costs globally (Ch. 7: Ecosystems, Invasive Species). As environmental conditions change further, mismatches between species and the availability of the resources they need to survive are expected to occur (Ch. 7: Ecosystems, KM 2). Without significant reductions in global greenhouse gas emissions, extinctions and transformative impacts on some ecosystems cannot be avoided in the long term (Ch. 9: Oceans, KM 1). While some new opportunities may emerge from ecosystem changes, economic and recreational opportunities and cultural heritage based around historical use of species or natural resources in many areas are at risk (Ch. 7: Ecosystems, KM 3; Ch. 18: Northeast, KMs 1 and 2, Box 18.6).

Ocean warming and acidification pose high and growing risks for many marine organisms, and the impacts of climate change on ocean ecosystems are expected to lead to reductions in important ecosystem services such as aquaculture, fishery productivity, and recreational opportunities (Ch 9: Oceans, KM 2). While climate change impacts on ocean ecosystems are widespread, the scope of ecosystem impacts occurring in tropical and polar areas is greater than anywhere else in the world. Ocean warming is already leading to reductions in vulnerable coral reef and sea ice habitats that support the livelihoods of many communities (Ch. 9: Oceans, KM 1). Decreasing sea ice extent in the Arctic represents a direct loss of important habitat for marine mammals, causing declines in their populations (Figure 1.2f) (Ch. 26: Alaska, Box 26.1). Changes in spring ice melt have affected the ability of coastal communities in Alaska to meet their walrus harvest needs in recent years (Ch. 26: Alaska, KM 1). These changes are expected to continue as sea ice declines further (Ch. 2: Climate, KM 7). In the tropics, ocean warming has already led to widespread coral reef bleaching and/or outbreaks of coral diseases off the coastlines of Puerto

Severe Coral Bleaching Projected for Hawai‘i and the U.S.-Affiliated Pacific Islands

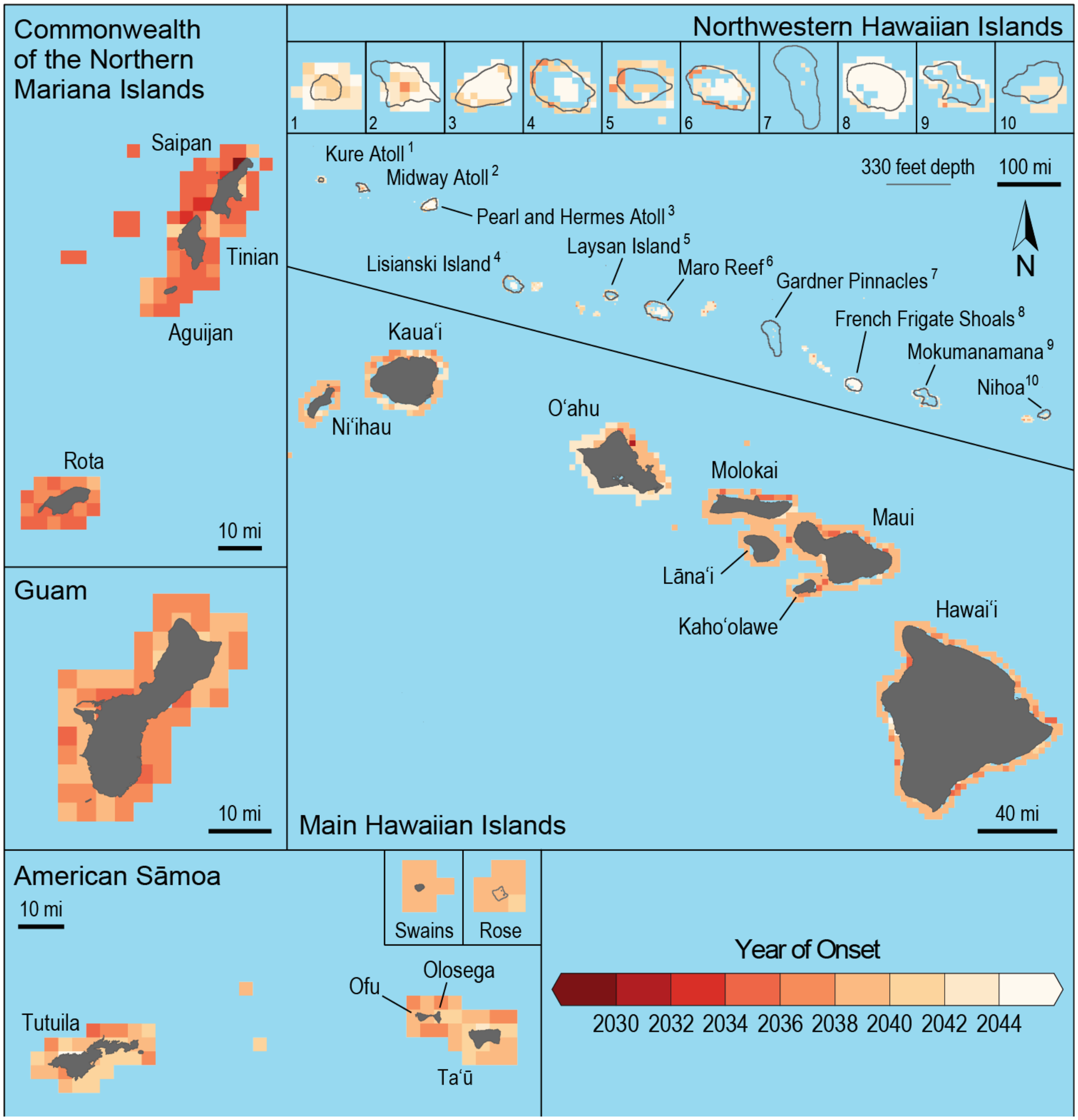


Figure 1.14: The figure shows the years when severe coral bleaching is projected to occur annually in the Hawai‘i and U.S.-Affiliated Pacific Islands region under a higher scenario (RCP8.5). Darker colors indicate earlier projected onset of coral bleaching. Under projected warming of approximately 0.5°F per decade, all nearshore coral reefs in the region will experience annual bleaching before 2050. *From Figure 27.10, Ch. 27: Hawai‘i (Source: NOAA).*

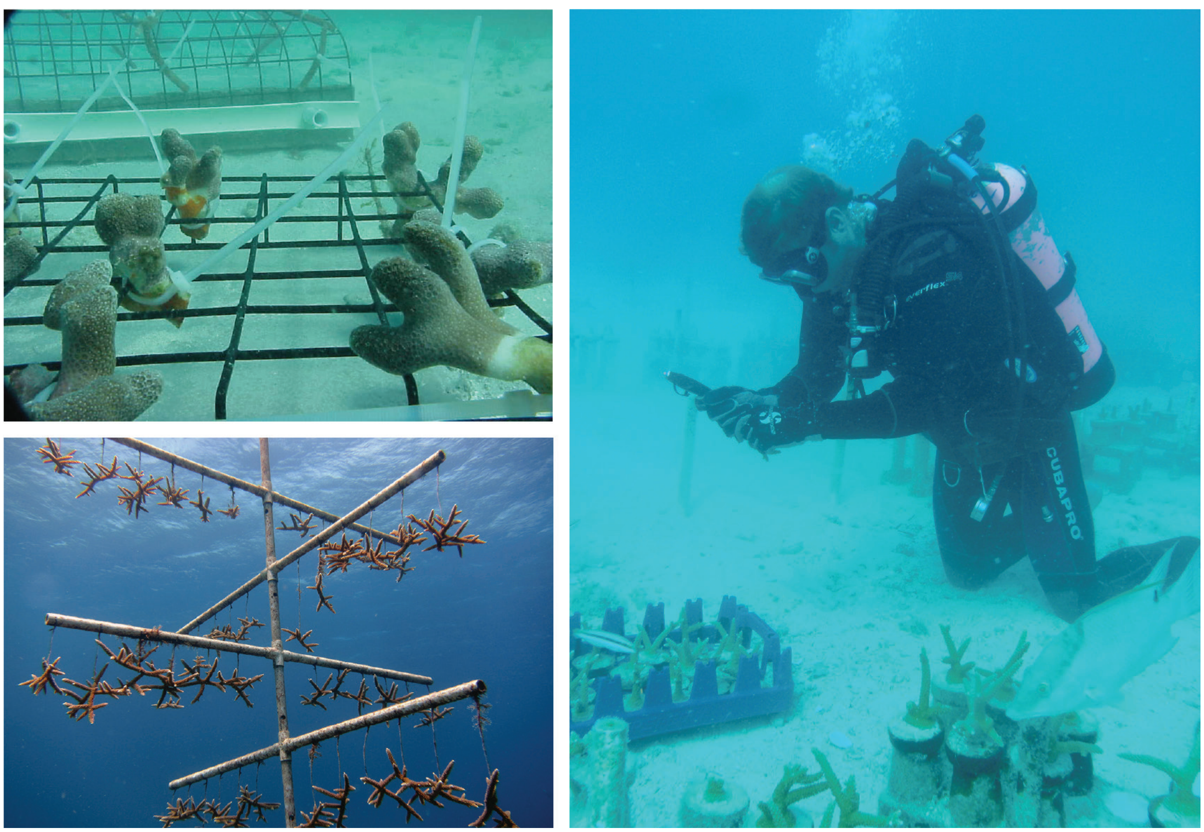
Rico, the U.S. Virgin Islands, Florida, and Hawai‘i and the U.S.-Affiliated Pacific Islands (Ch. 20: U.S. Caribbean, KM 2; Ch. 27: Hawai‘i & Pacific Islands, KM 4). By mid-century, widespread coral bleaching is projected to occur annually in Hawai‘i and the U.S.-Affiliated Pacific Islands (Figure 1.14). Bleaching and ocean acidification are expected to result in loss of reef structure, leading to lower fisheries yields and loss of coastal protection and habitat, with impacts on

tourism and livelihoods in both regions (Ch. 20: U.S. Caribbean, KM 2; Ch. 27: Hawaiʻi & Pacific Islands, KM 4). While some targeted response actions are underway (Figure 1.15), many impacts, including losses of unique coral reef and sea ice ecosystems, can only be avoided by significantly reducing global greenhouse gas emissions, particularly carbon dioxide (Ch. 9: Oceans, KM 1).

Human Health and Well-Being

Higher temperatures, increasing air quality risks, more frequent and intense extreme weather and climate-related events, increases in coastal flooding, disruption of ecosystem services, and other changes increasingly threaten the health and well-being of the American people, particularly populations that are already vulnerable. Future climate change is expected to further disrupt many areas of life, exacerbating existing challenges and revealing new risks to health and prosperity.

Rising temperatures pose a number of threats to human health and quality of life (Figure 1.16). High temperatures in the summer are linked directly to an increased risk of illness and death, particularly among older adults, pregnant women, and children (Ch. 18: Northeast, Box 18.3). With continued warming,



Promoting Coral Reef Recovery

Figure 1.15: Examples of coral farming in the U.S. Caribbean and Florida demonstrate different types of structures used for growing fragments from branching corals. Coral farming is a strategy meant to improve the reef community and ecosystem function, including for fish species. The U.S Caribbean Islands, Florida, Hawaiʻi, and the U.S.-Affiliated Pacific Islands face similar threats from coral bleaching and mortality due to warming ocean surface waters and ocean acidification. Degradation of coral reefs is expected to negatively affect fisheries and the economies that depend on them as habitat is lost in both regions. While coral farming may provide some targeted recovery, current knowledge and efforts are not nearly advanced enough to compensate for projected losses from bleaching and acidification. *From Figure 20.11, Ch. 20: U.S. Caribbean (Photo credits: [top left] Carlos Pacheco, U.S. Fish and Wildlife Service; [bottom left] NOAA; [right] Florida Fish and Wildlife).*

Projected Change in Very Hot Days by 2100 in Phoenix, Arizona

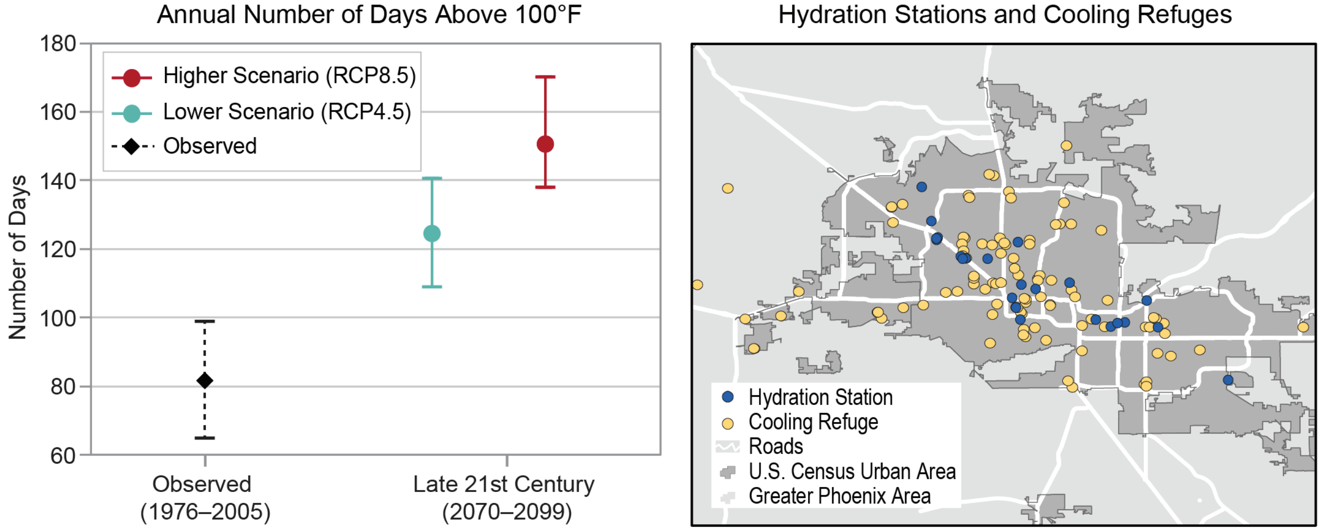


Figure 1.16: *(*left) The chart shows the average annual number of days above 100°F in Phoenix, Arizona, for 1976–2005, and projections of the average number of days per year above 100°F through the end of the 21st century (2070–2099) under the lower (RCP4.5) and higher (RCP8.5) scenarios. Dashed lines represent the 5th–95th percentile range of annual observed values. Solid lines represent the 5th–95th percentile range of projected model values. (right) The map shows hydration stations and cooling refuges (cooled indoor locations that provide water and refuge from the heat during the day) in Phoenix in August 2017. Such response measures for high heat events are expected to be needed at greater scales in the coming years if the adverse health effects of more frequent and severe heat waves are to be minimized. *Sources: (left) NOAA NCEI, CICS-NC, and LMI; (right) adapted from Southwest Cities Heat Refuges (a project by Arizona State University's Resilient Infrastructure Lab), available at http://www.coolme.today/#phoenix. Data provided by Andrew Fraser and Mikhail Chester, Arizona State University.*

cold-related deaths are projected to decrease and heat-related deaths are projected to increase. In most regions, the increases in heat-related deaths are expected to outpace the reductions in cold-related deaths (Ch. 14: Human Health, KM 1). Rising temperatures are expected to reduce electricity generation capacity while increasing energy demands and costs, which can in turn lead to power outages and blackouts (Ch. 4: Energy, KM 1; Ch. 11: Urban, Regional Summary, Figure 11.2). These changes strain household budgets, increase people's exposure to heat, and limit delivery of medical and social services. Risks from heat stress are higher for people without access to housing with sufficient insulation or air conditioning (Ch. 11: Urban, KM 1).

Changes in temperature and precipitation can increase air quality risks from wildfire and ground-level ozone (smog). Projected increases in wildfire activity due to climate change would further degrade air quality, resulting in increased health risks and impacts on quality of life (Ch. 13: Air Quality, KM 2; Ch. 14: Human Health, KM 1). Unless counteracting efforts to improve air quality are implemented, climate change is expected to worsen ozone pollution across much of the country, with adverse impacts on human health (Figure 1.21) (Ch. 13: Air Quality, KM 1). Earlier spring arrival, warmer temperatures, changes in precipitation, and higher carbon dioxide concentrations can also increase exposure to airborne pollen allergens. The frequency and severity of allergic illnesses, including asthma and hay fever, are expected to increase as a result of a changing climate (Ch. 13: Air Quality, KM 3).

Rising air and water temperatures and changes in extreme weather and climate-related events are expected to increase exposure to

waterborne and foodborne diseases, affecting food and water safety. The geographic range and distribution of disease-carrying insects and pests are projected to shift as climate changes, which could expose more people in North America to ticks that carry Lyme disease and mosquitoes that transmit viruses such as West Nile, chikungunya, dengue, and Zika (Ch. 14: Human Health, KM 1; Ch. 16: International, KM 4).

Mental health consequences can result from exposure to climate- or extreme weather-related events, some of which are projected to intensify as warming continues (Ch. 14: Human Health, KM 1). Coastal city flooding as a result of sea level rise and hurricanes, for example, can result in forced evacuation, with adverse effects on family and community stability as well as mental and physical health (Ch. 11: Urban, KM 1). In urban areas, disruptions in food supply or safety related to extreme weather or climate-related events are expected to disproportionately impact those who already experience food insecurity (Ch. 11: Urban, KM 3).

Indigenous peoples have historical and cultural relationships with ancestral lands, ecosystems, and culturally important species that are threatened by climate change (Ch. 15: Tribes, KM 1; Ch. 19: Southeast, KM 4, Case Study "Mountain Ramps"; Ch. 24: Northwest, KM 5). Climate change is expected to compound existing physical health issues in Indigenous communities, in part due to the loss of traditional foods and practices, and in some cases, the mental stress from permanent community displacement (Ch. 14: Human Health, KM 2; Ch. 15: Tribes, KM 2). Throughout the United States, Indigenous peoples are considering or actively pursuing relocation as an adaptation strategy in response to climate-related disasters, more frequent flooding, loss of land due to erosion, or as livelihoods are compromised by ecosystem shifts linked to climate change (Ch. 15: Tribes, KM 3). In Louisiana, a federal grant is being used to relocate the tribal community of Isle de Jean Charles in response to severe land loss, sea level rise, and coastal flooding (Figure 1.17) (Ch. 19: Southeast, KM 2, Case Study "A Lesson Learned for Community Resettlement"). In Alaska, coastal Native communities are already

Community Relocation—Isle de Jean Charles, Louisiana

Figure 1.17: (left) A federal grant is being used to relocate the tribal community of Isle de Jean Charles, Louisiana, in response to severe land loss, sea level rise, and coastal flooding. *From Figure 15.3, Ch. 15: Tribes (Photo credit: Ronald Stine)*. (right) As part of the resettlement of the tribal community of Isle de Jean Charles, residents are working with the Lowlander Center and the State of Louisiana to finalize a plan that reflects the desires of the community. *From Figure 15.4, Ch. 15: Tribes (Photo provided by Louisiana Office of Community Development)*.

Adaptation Measures in Kivalina, Alaska

Figure 1.18: A rock revetment was installed in the Alaska Native Village of Kivalina in 2010 to reduce increasing risks from erosion. A new rock revetment wall has a projected lifespan of 15 to 20 years. *From Figure 15.3, Ch. 15: Tribes (Photo credit: ShoreZone. Creative Commons License CC BY 3.0: https://creativecommons.org/licenses/by/3.0/legalcode).* The inset shows a close-up of the rock wall in 2011. *Photo credit: U.S. Army Corps of Engineers–Alaska District.*

experiencing heightened erosion driven by declining sea ice, rising sea levels, and warmer waters (Figure 1.18). Coastal and river erosion and flooding in some cases will require parts of communities, or even entire communities, to relocate to safer terrain (Ch. 26: Alaska, KM 2). Combined with other stressors, sea level rise, coastal storms, and the deterioration of coral reef and mangrove ecosystems put the long-term habitability of coral atolls in the Hawai‘i and U.S.-Affiliated Pacific Islands region at risk, introducing issues of sovereignty, human and national security, and equity (Ch. 27: Hawai‘i & Pacific Islands, KM 6).

Reducing the Risks of Climate Change

Climate change is projected to significantly affect human health, the economy, and the environment in the United States, particularly in futures with high greenhouse gas emissions and limited or no adaptation. Recent findings reinforce the fact that without substantial and sustained reductions in greenhouse gas emissions and regional adaptation efforts, there will be substantial and far-reaching changes over the course of the 21st century with negative consequences for a large majority of sectors, particularly towards the end of the century.

The impacts and costs of climate change are already being felt in the United States, and changes in the likelihood or severity of some recent extreme weather events can now be attributed with increasingly higher confidence to human-caused warming (see CSSR, Ch. 3). Impacts associated with human health, such as premature deaths due to extreme temperatures and poor air quality, are some of the most

Box 1.4: How Climate Change Around the World Affects the United States

The impacts of changing weather and climate patterns beyond U.S. international borders affect those living in the United States, often in complex ways that can generate both challenges and opportunities. The International Chapter (Ch. 16), new to this edition of the NCA, assesses our current understanding of how global climate change, natural variability, and associated extremes are expected to impact—and in some cases are already impacting—U.S. interests both within and outside of our borders.

Current and projected climate-related impacts on our economy include increased risks to overseas operations of U.S. businesses, disruption of international supply chains, and shifts in the availability and prices of commodities. For example, severe flooding in Thailand in 2011 disrupted the supply chains for U.S. electronics manufacturers (Ch. 16: International, Figure 16.1). U.S. firms are increasingly responding to climate-related risks, including through their financial disclosures and partnerships with environmental groups (Ch. 16: International, KM 1).

Impacts from climate-related events can also undermine U.S. investments in international development by slowing or reversing social and economic progress in developing countries, weakening foreign markets for U.S. exports, and increasing the need for humanitarian assistance and disaster relief efforts. Predictive tools can help vulnerable countries anticipate natural disasters, such as drought, and manage their impacts. For example, the United States and international partners created the Famine Early Warning Systems Network (FEWS NET), which helped avoid severe food shortages in Ethiopia during a historic drought in 2015 (Ch. 16: International, KM 2).

Natural variability and changes in climate increase risks to our national security by affecting factors that can exacerbate conflict and displacement outside of U.S. borders, such as food and water insecurity and commodity price shocks. More directly, our national security is impacted by damage to U.S. military assets such as roads, runways, and waterfront infrastructure from extreme weather and climate-related events (Figures 1.8 and 1.9). The U.S. military is working to both fully understand these threats and incorporate projected climate changes into long-term planning. For example, the Department of Defense has performed a comprehensive scenario-driven examination of climate risks from sea level rise to all of its coastal military sites, including atolls in the Pacific Ocean (Ch. 16: International, KM 3).

Finally, the impacts of climate change are already affecting the ecosystems that span our Nation's borders and the communities that rely on them. International frameworks for the management of our shared resources continue to be restructured to incorporate risks from these impacts. For example, a joint commission that implements water treaties between the United States and Mexico is exploring adaptive water management strategies that account for the effects of climate change and natural variability on Colorado River water (Ch. 16: International, KM 4).

substantial (Ch. 13: Air Quality, KM 1; Ch. 14: Human Health, KMs 1 and 4; Ch 29: Mitigation, KM 2). While many sectors face large economic risks from climate change, other impacts can have significant implications for societal or cultural resources. Further, some impacts will very likely be irreversible for thousands of years, including those to species, such as corals (Ch. 9: Oceans, KM 1; Ch. 27: Hawai‘i & Pacific Islands, KM 4), or that involve the crossing of thresholds, such as the effects of ice sheet disintegration on accelerated sea level

rise, leading to widespread effects on coastal development lasting thousands of years (Ch. 29: Mitigation, KM 2).

Future impacts and risks from climate change are directly tied to decisions made in the present, both in terms of mitigation to reduce emissions of greenhouse gases (or remove carbon dioxide from the atmosphere) and adaptation to reduce risks from today's changed climate conditions and prepare for future impacts. Mitigation and adaptation activities can be considered complementary strategies—mitigation efforts can reduce future risks, while adaptation actions can minimize the consequences of changes that are already happening as a result of past and present greenhouse gas emissions.

Many climate change impacts and economic damages in the United States can be substantially reduced through global-scale reductions in greenhouse gas emissions complemented by regional and local adaptation efforts (Ch 29: Mitigation, KM 4). Our understanding of the magnitude and timing of risks that can be avoided varies by sector, region, and assumptions about how adaptation measures change the exposure and vulnerability of people, livelihoods, ecosystems, and infrastructure. Acting sooner rather than later generally results in lower costs overall for both adaptation and mitigation efforts and can offer other benefits in the near term (Ch. 29: Mitigation, KM 3).

Since the Third National Climate Assessment (NCA3) in 2014, a growing number of states, cities, and businesses have pursued or expanded upon initiatives aimed at reducing greenhouse gas emissions, and the scale of adaptation implementation across the country has increased. However, these efforts do not yet approach the scale needed to avoid substantial damages to the economy, environment, and human health expected over the coming decades (Ch. 28: Adaptation, KM 1; Ch. 29: Mitigation, KMs 1 and 2).

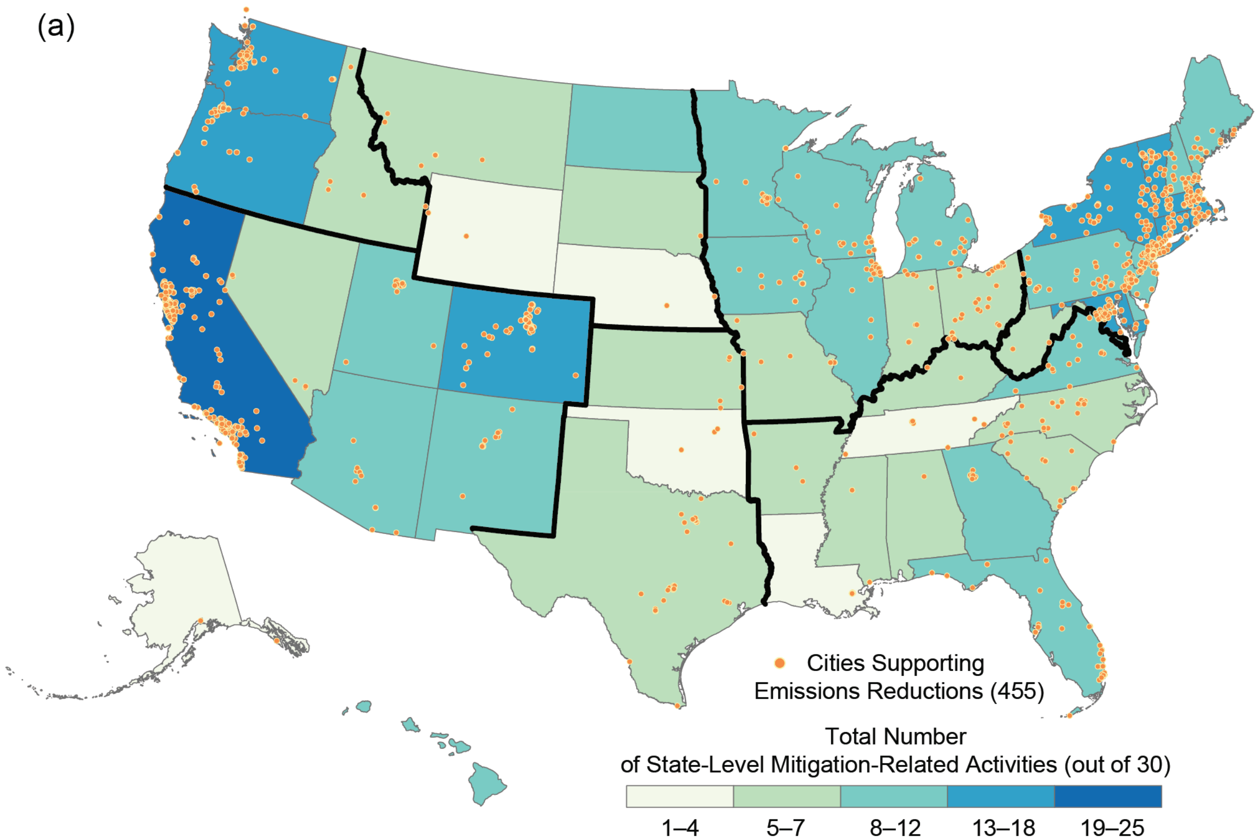
Mitigation

Many activities within the public and private sectors aim for or have the effect of reducing greenhouse gas emissions, such as the increasing use of natural gas in place of coal or the expansion of wind and solar energy to generate electricity. Fossil fuel combustion accounts for approximately 85% of total U.S. greenhouse gas emissions, with agriculture, land-cover change, industrial processes, and methane from fossil fuel extraction and processing as well as from waste (including landfills, wastewater treatment, and composting) accounting for most of the remainder. A number of efforts exist at the federal level to promote low-carbon energy technologies and to increase soil and forest carbon storage.

State, local, and tribal government approaches to mitigating greenhouse gas emissions include comprehensive emissions reduction strategies as well as sector- and technology-specific policies (see Figure 1.19). Since NCA3, private companies have increasingly reported their greenhouse gas emissions, announced emissions reductions targets, implemented actions to achieve those targets, and, in some cases, even put an internal price on carbon. Individuals and other organizations are also making choices every day to reduce their carbon footprints.

Market forces and technological change, particularly within the electric power sector, have contributed to a decline in U.S. greenhouse gas emissions over the past decade. In 2016, U.S.

Mitigation-Related Activities at State and Local Levels



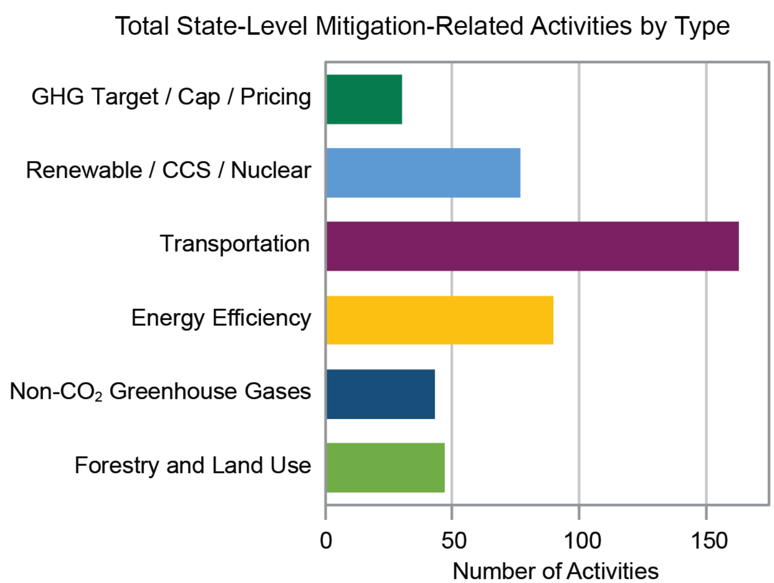


Figure 1.19: (a) The map shows the number of mitigation-related activities at the state level (out of 30 illustrative activities) as well as cities supporting emissions reductions; (b) the chart depicts the type and number of activities by state. Several territories also have a variety of mitigation-related activities, including American Sāmoa, the Federated States of Micronesia, Guam, Northern Mariana Islands, Puerto Rico, and the U.S. Virgin Islands. *From Figure 29.1, Ch. 29: Mitigation (Sources: [a] EPA and ERT, Inc. [b] adapted from America's Pledge 2017)*.

emissions were at their lowest levels since 1994. Power sector emissions were 25% below 2005 levels in 2016, the largest emissions reduction for a sector of the American economy over this time. This decline was in large part due to increases in natural gas and renewable energy generation, as well as enhanced energy efficiency standards and programs (Ch. 4: Energy, KM 2). Given these advances in electricity generation, transmission, and distribution, the largest annual sectoral emissions in the United States now come from transportation. As of the writing of this report, business-as-usual (as in, no new policies) projections of U.S. carbon dioxide and other greenhouse gas emissions show flat or declining trajectories over the next decade with a central estimate of about 15% to 20% reduction below 2005 levels by 2025 (Ch. 29: Mitigation, KM 1).

Recent studies suggest that some of the indirect effects of mitigation actions could significantly reduce—or possibly even completely offset—the potential costs associated with cutting greenhouse gas emissions. Beyond reduction of climate pollutants, there are many benefits, often immediate, associated with greenhouse gas emissions reductions, such as improving air quality and public health, reducing crop damages from ozone, and increasing energy independence and security through increased reliance on domestic sources of energy (Ch. 13: Air Quality, KM 4; Ch. 29: Mitigation, KM 4).

Adaptation

Many types of adaptation actions exist, including changes to business operations, hardening infrastructure against extreme weather, and adjustments to natural resource management strategies. Achieving the benefits of adaptation can require upfront investments to achieve longer-term savings, engaging with different stakeholder interests and values, and planning under uncertainty. In many sectors, adaptation can reduce the cost of climate impacts by more than half (Ch. 28: Adaptation, KM 4; Ch. 29: Mitigation, KM 4).

At the time of NCA3's release in 2014, its authors found that risk assessment and planning were underway throughout the United States but that on-the-ground implementation was limited. Since then, the scale and scope of adaptation implementation has increased, including by federal, state, tribal, and local agencies as well as business, academic, and nonprofit organizations (Figure 1.20). While the level of implementation is now higher, it is not yet common nor uniform across the United States, and the scale of implementation for some effects and locations is often considered inadequate to deal with the projected scale of climate change risks. Communities have generally focused on actions that address risks from current climate variability and recent extreme events, such as making buildings and other assets incrementally less sensitive to climate impacts. Fewer communities have focused on actions to address the anticipated scale of future change and emergent threats, such as reducing exposure by preventing building in high-risk locations or retreating from at-risk coastal areas (Ch. 28: Adaptation, KM 1).

Many adaptation initiatives can generate economic and social benefits in excess of their costs in both the near and long term (Ch. 28: Adaptation, KM 4). Damages to infrastructure, such as road and rail networks, are particularly sensitive to adaptation assumptions, with proactive measures that account for future climate risks estimated to be capable of reducing damages by large fractions. More than half of damages to coastal property are estimated to

Figure 1.20: Adaptation entails a continuing risk management process. With this approach, individuals and organizations become aware of and assess risks and vulnerabilities from climate and other drivers of change, take actions to reduce those risks, and learn over time. The gray arced lines compare the current status of implementing this process with the status reported by the Third National Climate Assessment in 2014; darker color indicates more activity. *From Figure 28.1, Ch. 28: Adaptation (Source: adapted from National Research Council, 2010. Used with permission from the National Academies Press, © 2010, National Academy of Sciences. Image credits, clockwise from top: National Weather Service; USGS; Armando Rodriguez, Miami-Dade County; Dr. Neil Berg, MARISA; Bill Ingalls, NASA).*

be avoidable through adaptation measures such as shoreline protection and beach replenishment (Ch. 29: Mitigation, KM 4). Considerable guidance is available on actions whose benefits exceed their costs in some sectors (such as adaptation responses to storms and rising seas in coastal zones, to riverine and extreme precipitation flooding, and for agriculture at the farm level), but less so on other actions (such as those aimed at addressing risks to health, biodiversity, and ecosystems services) that may provide significant benefits but are not as well understood (Ch. 28: Adaptation, KM 4).

Effective adaptation can also enhance social welfare in many ways that can be difficult to quantify, including improving economic opportunity, health, equity, national security, education, social connectivity, and sense of place, while safeguarding cultural resources

and enhancing environmental quality. Aggregating these benefits into a single monetary value is not always the best approach, and more fundamentally, communities may value benefits differently. Considering various outcomes separately in risk management processes can facilitate participatory planning processes and allow for a specific focus on equity. Prioritizing adaptation actions for populations that face higher risks from climate change, including low-income and marginalized communities, may prove more equitable and lead, for instance, to improved infrastructure in their communities and increased focus on efforts to promote community resilience that can improve their capacity to prepare for, respond to, and recover from disasters (Ch. 28: Adaptation, KM 4).

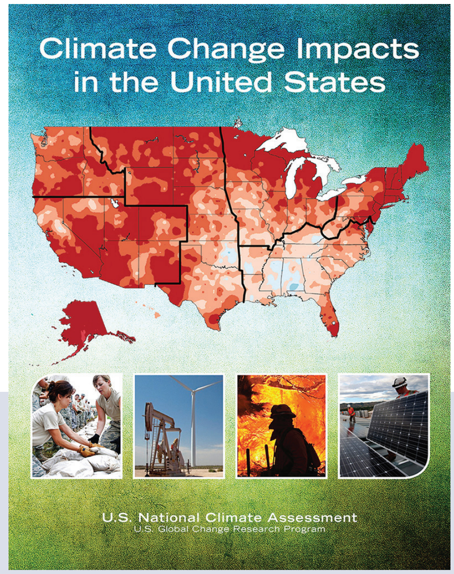
A significant portion of climate risk can be addressed by integrating climate adaptation into existing investments, policies, and practices. Integration of climate adaptation into decision processes has begun in many areas including financial risk reporting, capital investment planning, engineering standards, military planning, and disaster risk management. A growing number of jurisdictions address climate risk in their land-use, hazard mitigation, capital improvement, and transportation plans, and a small number of cities explicitly link their coastal and hazard mitigation plans using analysis of future climate risks. However, over the course of this century and especially under a higher scenario (RCP8.5), reducing the risks of climate change may require more significant changes to policy and regulations at all scales, community planning, economic and financial systems, technology applications, and ecosystems (Ch. 28: Adaptation, KM 5).

Some sectors are already taking actions that go beyond integrating climate risk into current practices. Faced with substantial climate-induced changes in the future, including new invasive species and shifting ranges for native species, ecosystem managers have already begun to adopt new approaches such as assisted migration and development of wildlife corridors (Ch. 7: Ecosystems, KM 2). Many millions of Americans live in coastal areas threatened by sea level rise; in all but the very lowest sea level rise projections, retreat will become an unavoidable option in some areas along the U.S. coastline (Ch. 8: Coastal, KM 1). The Federal Government has granted funds for the relocation of some communities, including the Biloxi-Chitimacha-Choctaw Tribe from Isle de Jean Charles in Louisiana (Figure 1.17). However, the potential need for millions of people and billions of dollars of coastal infrastructure to be relocated in the future creates challenging legal, financial, and equity issues that have not yet been addressed (Ch. 28: Adaptation, KM 5).

In some areas, lack of historical or current data to inform policy decisions can be a limitation to assessments of vulnerabilities and/or effective adaptation planning. For this National Climate Assessment, this was particularly the case for some aspects of the Alaska, U.S. Caribbean, and Hawai'i and U.S.-Affiliated Pacific Islands regions. In many instances, relying on Indigenous knowledges is among the only current means of reconstructing what has happened in the past. To help communities across the United States learn from one another in their efforts to build resilience to a changing climate, this report highlights common climate-related risks and possible response actions across all regions and sectors.

What Has Happened Since The Last National Climate Assessment?

Our understanding of and experience with climate science, impacts, risks, and adaptation in the United States have grown significantly since the Third National Climate Assessment (NCA3), advancing our knowledge of key processes in the earth system, how human and natural forces are changing them, what the implications are for society, and how we can respond.



Key Scientific Advances

Detection and Attribution: Significant advances have been made in the attribution of the human influence for individual climate and weather extreme events (see CSSR, Chs. 3, 6, 7, and 8).

Extreme Events and Atmospheric Circulation: How climate change may affect specific types of extreme events in the United States and the extent to which atmospheric circulation in the midlatitudes is changing or is projected to change, possibly in ways not captured by current climate models, are important areas of research where scientific understanding has advanced (see CSSR, Chs. 5, 6, 7, and 9).

Localized Information: As computing resources have grown, projections of future climate from global models are now being conducted at finer scales (with resolution on the order of 15 miles), providing more realistic characterization of intense weather systems, including hurricanes. For the first time in the NCA process, sea level rise projections incorporate geographic variation based on factors such as local land subsidence, ocean currents, and changes in Earth's gravitational field (see CSSR, Chs. 9 and 12).

Ocean and Coastal Waters: Ocean acidification, warming, and oxygen loss are all increasing, and scientific understanding of the severity of their impacts is growing. Both oxygen loss and acidification may be magnified in some U.S. coastal waters relative to the global average, raising the risk of serious ecological and economic consequences (see CSSR, Chs. 2 and 13).

Rapid Changes for Ice on Earth: New observations from many different sources confirm that ice loss across the globe is continuing and, in many cases, accelerating. Since NCA3, Antarctica and Greenland have continued to lose ice mass, with mounting evidence that mass loss is accelerating. Observations continue to show declines in the volume of mountain glaciers around the world. Annual September minimum sea ice extent in the Arctic Ocean has decreased at a rate of 11%–16% per decade since the early 1980s, with accelerating ice loss since 2000. The annual sea ice extent minimum for 2016 was the second lowest on record; the sea ice minimums in 2014 and 2015 were also among the lowest on record (see CSSR, Chs. 1, 11, and 12).

Potential Surprises: Both large-scale shifts in the climate system (sometimes called "tipping points") and compound extremes have the potential to generate outcomes that are difficult to anticipate and may have high consequences. The more the climate changes, the greater the potential for these surprises (see CSSR, Ch. 15).

Extreme Events

Climate change is altering the characteristics of many extreme weather and climate-related events. Some extreme events have already become more frequent, intense, widespread, or of longer duration, and many are expected to continue to increase or worsen, presenting substantial challenges for built, agricultural, and natural systems. Some storm types such as hurricanes, tornadoes, and winter storms are also exhibiting changes that have been linked to climate change, although the current state of the science does not yet permit detailed understanding (see CSSR, Executive Summary). Individual extreme weather and climate-related events—even those that have not been clearly attributed to climate change by scientific analyses—reveal risks to society and vulnerabilities that mirror those we expect in a warmer world. Non-climate stressors (such as land-use changes and shifting demographics) can also amplify the damages associated with extreme events. The National Oceanic and Atmospheric Administration estimates that the United States has experienced 44 billion-dollar weather and climate disasters since 2015 (through April 6, 2018), incurring costs of nearly $400 billion (https://www.ncdc.noaa.gov/billions/).

Hurricanes: The 2017 Atlantic Hurricane season alone is estimated to have caused more than $250 billion in damages and over 250 deaths throughout the U.S. Caribbean, Southeast, and Southern Great Plains. More than 30 inches of rain fell during Hurricane Harvey, affecting 6.9 million people. Hurricane Maria's high winds caused widespread devastation to Puerto Rico's transportation, agriculture, communication, and energy infrastructure. Extreme rainfall of up to 37 inches caused widespread flooding and mudslides

Damage from Hurricane Maria in San Juan, Puerto Rico
Photo taken during a reconnaissance flight of the island on September 23, 2017. *Photo credit: Sgt. Jose Ahiram Diaz-Ramos, Puerto Rico National Guard.*

across the island. The interruption to commerce and standard living conditions will be sustained for a long period while much of Puerto Rico's infrastructure is rebuilt. Hurricane Irma destroyed 25% of buildings in the Florida Keys.

Floods: In August 2016, a historic flood resulting from 20 to 30 inches of rainfall over several days devastated a large area of southern Louisiana, causing over $10 billion in damages and 13 deaths. More than 30,000 people were rescued from floodwaters that damaged or destroyed more than 50,000 homes, 100,000 vehicles, and 20,000 businesses. In June 2016, torrential rainfall caused destructive flooding throughout many West Virginia towns, damaging thousands of homes and businesses and causing considerable loss of life. More than 1,500 roads and bridges were damaged or destroyed. The 2015–2016 El Niño poured 11 days of record-setting rainfall on Hawai‘i, causing severe urban flooding.

Drought: In 2015, drought conditions caused about $5 billion in damages across the Southwest and Northwest, as well as parts of the Northern Great Plains. California experienced the most severe drought conditions. Hundreds of thousands of acres of farmland remained fallow, and excess groundwater pumping was required to irrigate existing agricultural interests. Two years later, in 2017, extreme drought caused $2.5 billion in agricultural

The Deadly Carr Fire

The Carr Fire (as seen over Shasta County, California, on August 4, 2018) damaged or destroyed more than 1,500 structures and resulted in several fatalities. *Photo credit: Sgt. Lani O. Pascual, U.S. Army National Guard.*

damages across the Northern Great Plains. Field crops, including wheat, were severely damaged, and the lack of feed for cattle forced ranchers to sell off livestock.

Wildfires: During the summer of 2015, over 10.1 million acres—an area larger than the entire state of Maryland—burned across the United States, surpassing 2006 for the highest annual total of U.S. acreage burned since record keeping began in 1960. These wildfire conditions were exacerbated by the preceding drought conditions in several states. The most extensive wildfires occurred in Alaska, where 5 million acres burned within the state. In Montana, wildfires burned in excess of 1 million acres. The costliest wildfires occurred in California, where more than 2,500 structures were destroyed by the Valley and Butte Fires; insured losses alone exceeded $1 billion. In October 2017, a historic firestorm damaged or destroyed more than 15,000 homes, businesses, and other structures across California (see Figure 1.5). The Tubbs, Atlas, Nuns, and Redwood Valley Fires caused a total of 44 deaths and their combined destruction represents the costliest wildfire event on record.

Tornadoes: In March 2017, a severe tornado outbreak caused damage across much of the Midwest and into the Northeast. Nearly 1 million customers lost power in Michigan alone due to sustained high winds, which affected several states from Illinois to New York.

Heat Waves: Honolulu experienced 24 days of record-setting heat during the 2015–2016 El Niño event. As a result, the local energy utility issued emergency public service announcements to curtail escalating air conditioning use that threatened the electrical grid.

New Aspects of this Report

Hundreds of states, counties, cities, businesses, universities, and other entities are implementing actions that build resilience to climate-related impacts and risks, while also aiming to reduce greenhouse gas emissions. Many of these actions have been informed by new climate-related tools and products developed through the U.S. Global Change Research Program (USGCRP) since NCA3 (see Appendix 3: Scenario Products & Data Tools); we briefly highlight a few of them here. In addition, several structural changes have been introduced to the report and new methods used in response to stakeholder needs for more localized information and to address key gaps identified in NCA3. The Third National Climate Assessment remains a valuable and relevant resource—this report expands upon our knowledge and experience as presented four years ago.

Climate Science Special Report: Early in the development of NCA4, experts and Administration officials recognized that conducting a comprehensive physical science assessment (Volume I) in advance of an impacts assessment (Volume II) would allow one to inform the other. The *Climate Science Special Report*, released in November 2017, is Volume I of NCA4 and represents the most thorough and up-to-date assessment of climate science in the United States and underpins the findings of this report; its findings are summarized in Chapter 2 (Our Changing Climate). See the "Key Scientific Advances" section in this box and Box 2.3 in Chapter 2 for more detail.

Scenario Products: As described in more detail in Appendix 3 (Data Tools & Scenario Products), federal interagency groups developed a suite of high-resolution scenario products that span a range of plausible future changes in key environmental variables through at least 2100. These USGCRP scenario products help ensure consistency across the report and improve the ability to synthesize across chapters. Where possible, authors have used these scenario products to frame uncertainty in future climate as it relates to the risks that are the focus of their chapters. In addition, the Indicators Interagency Working Group has developed an Indicators platform that uses observations or calculations to monitor conditions or trends in the earth system, just as businesses might use the unemployment index

as an indicator of economic conditions (see Figure 1.2 and https://www.globalchange.gov/browse/indicators).

Localized Information: With the increased focus on local and regional information in NCA4, USGCRP agencies developed two additional products that not only inform this assessment but can serve as valuable decision-support tools. The first are the State Climate Summaries—a peer-reviewed collection of climate change information covering all ten NCA4 regions at the state level. In addition to standard data on observed and projected climate change, each State Climate Summary contains state-specific changes and their related impacts as well as a suite of complementary graphics (stateclimatesummaries.globalchange.gov). The second product is the U.S. Climate Resilience Toolkit (https://toolkit.climate.gov/), which offers data-driven tools, information, and subject-matter expertise from across the Federal Government in one easy-to-use location, so Americans are better able to understand the climate-related risks and opportunities impacting their communities and can make more informed decisions on how to respond. In particular, the case studies showcase examples of climate change impacts and accompanying response actions that complement those presented in Figure 1.1 and allow communities to learn how to build resilience from one another.

New Chapters: In response to public feedback on NCA3 and input solicited in the early stages of this assessment, a number of significant structural changes have been made. Most fundamentally, the balance of the report's focus has shifted from national-level chapters to regional chapters in response to a growing desire for more localized information on impacts. Building on this theme, the Great Plains chapter has been split into Northern and Southern chapters (Chapters 22 and 23) along the Kansas–Nebraska border. In addition, the U.S. Caribbean is now featured as a separate region in this report (Chapter 20), focusing on the unique impacts, risks, and response capabilities in Puerto Rico and the U.S. Virgin Islands.

Public input also requested greater international context in the report, which has been addressed through two new additions. A new chapter focuses on topics including the effects of climate change on U.S. trade and businesses, national security, and U.S. humanitarian assistance and disaster relief (Chapter 16). A new international appendix (Appendix 4) presents a number of illustrative examples of how other countries have conducted national climate assessments, putting our own effort into a global context.

Given recent scientific advances, some emerging topics warranted a more visible platform in NCA4. A new chapter on Air Quality (Chapter 13) examines how traditional air pollutants are affected by climate change. A new chapter on Sector Interactions, Multiple Stressors, and Complex Systems (Chapter 17) evaluates climate-related risks to interconnected

human and natural systems that are increasingly vulnerable to cascading impacts and highlights advances in analyzing how these systems will interact with and respond to a changing environment (see Box 1.3).

Integrating Economics: This report, to a much greater degree than previous National Climate Assessments, includes broader and more systematic quantification of climate change impacts in economic terms. While this is an emerging body of literature that is not yet reflected in each of the 10 NCA regions, it represents a valuable advancement in our understanding of the financial costs and benefits of climate change impacts. Figure 1.21 provides an illustration of the type of economic information that is integrated throughout this report. It shows the financial damages *avoided* under a lower scenario (RCP4.5) versus a higher scenario (RCP8.5).

New Economic Impact Studies

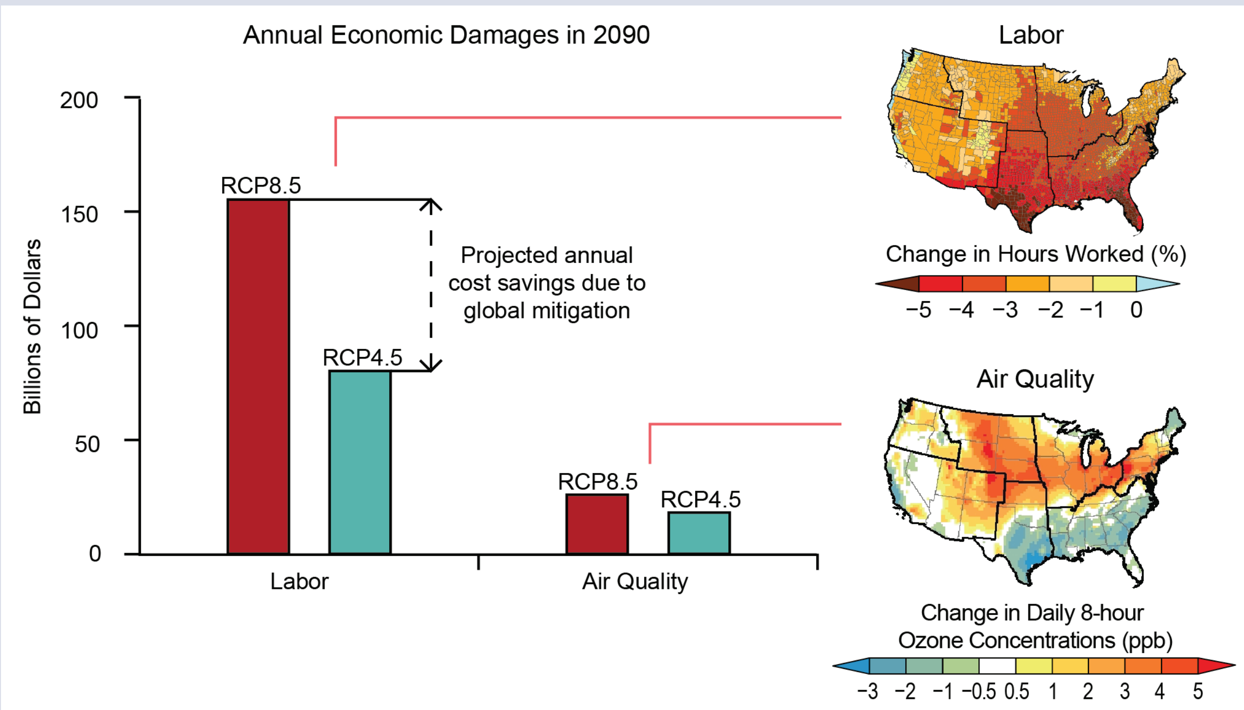
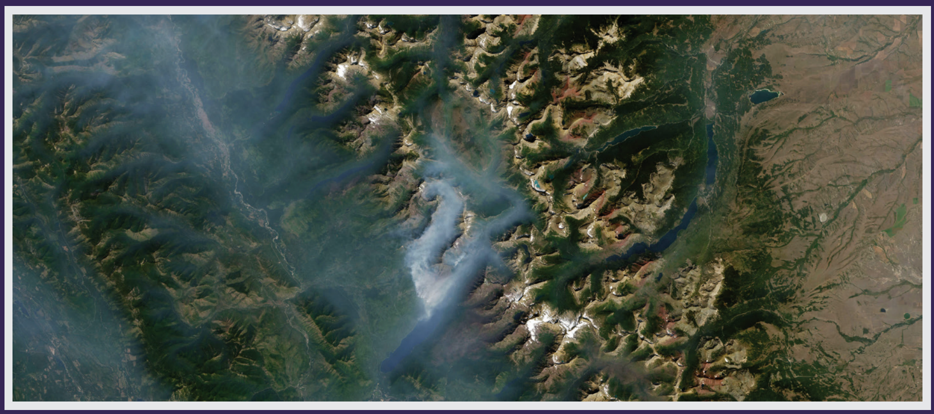


Figure 1.21: Annual economic impact estimates are shown for labor and air quality. The bar graph on the left shows national annual damages in 2090 (in billions of 2015 dollars) for a higher scenario (RCP8.5) and lower scenario (RCP4.5); the difference between the height of the RCP8.5 and RCP4.5 bars for a given category represents an estimate of the economic benefit to the United States from global mitigation action. For these two categories, damage estimates do not consider costs or benefits of new adaptation actions to reduce impacts, and they do not include Alaska, Hawai'i and U.S.-Affiliated Pacific Islands, or the U.S. Caribbean. The maps on the right show regioanal variation in annual impacts projected under the higher scenario (RCP8.5) in 2090. The map on the top shows the percent change in hours worked in high-risk industries as compared to the period 2003–2007. The hours lost result in economic damages: for example, $28 billion per year in the Southern Great Plains. The map on the bottom is the change in summer-average maximum daily 8-hour ozone concentrations (ppb) at ground-level as compared to the period 1995–2005. These changes in ozone concentrations result in premature deaths: for example, an additional 910 premature deaths each year in the Midwest. *Source: EPA, 2017. Multi-Model Framework for Quantitative Sectoral Impacts Analysis: A Technical Report for the Fourth National Climate Assessment. U.S. Environmental Protection Agency, EPA 430-R-17-001.*

This document responds to the requirements of Section 106 of the Global Change Research Act of 1990 (http://www.globalchange.gov/about/legal-mandate), and it meets all federal requirements associated with the *highly influential scientific assessment* (HISA) standard of the Information Quality Act (see Appendix 2: Information in the Fourth National Climate Assessment).



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For an assessment of the physical science (NCA4 Vol. I) underlying this report, visit:
science2017.globalchange.gov

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